BOSTON UNIVERSITY

GRADUATE SCHOOL

Thesis

AUTOMATIC CONTROL OF WIND ENERGY BY ELECTRICAL METHODS

by

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(B.S., Northeastern University, 1941)

submitted in partial fulfilment of the requirements for the degree of Master of Arts

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Topical Outline

List of Illustrations

I. Introduction.

The purpose of this thesis is to devise and describe in detail the underlying principles of a method of automatically controlling a sailing vessel which is travelling by wind energy. To operate such a ship, when under sail, one need only aim a small pointer, located near a compass on board ship, in the direction he wishes to travel. The automatic controls take care of the rest. They steer the ship onto, and hold her on the desired course. They also adjust the set of the sails for maximum driving power using the wind energy available. The ship will tack of her own accord when necessary to do so.

The first problem encountered is that of automatically controlling the sails so as to obtain maximum driving power from the wind energy on all points of sailing. The sails must be trimmed in, or slackened off for any fluctuations in direction of wind, as well as for any changes in direction of course.

The second problem encountered is that of making the ship automatically steer herself onto any desired course, and remain thereon. This requires one method of control when tacking, and another when not tacking.

The methods used to obtain the automatic control make use of bridge circuits, wherein the resistances of the branches

are dependent on wind direction, position of sails, and direction of course. Unbalanced conditions in the bridges result when either the wind shifts, or the course is changed, or the ship deviates from her course. Currents due to unbalance in the bridges are used as motor controls to reset the sails and to turn the rudder until the ship is again sailing properly. When the ship has been restored to her course, and the sails are set correctly, the bridges again become balanced, and the corrective automatic control ceases to operate.

Control of the motor which operates the rudder is obtained by utilizing a split-field reversing A.C. series motor, which is reversible in its direction by virtue of the double, or split, field. Phototubes and shield grid thyratrons provide an electronic control for this motor.

Thus the automatic controls do the work of running the ship, the steering, sail handling, and the tacking, while the navigator merely aims a small pointer in the direction he wishes his ship to travel.

II. Automatic Control of Angles Between Wind and Sail.

A. "Bird's Eye View"ofSail Control.

As a ship travels along under wind power her sails must be trimmed to just a certain angle in order to obtain the maximum drive from the energy of the wind. For each little shift in wind direction the alert skipper will readjust his sails to a new setting in order to maintain maximum speed.

Now let us consider a method whereby the sails of a ship may be automatically trimmed in or slackened off as the wind direction fluctuates. Assume that the course sailed is to remain unchanged. At the very tip of the mast is mounted a "pennant" which is used as an indicator of the apparent wind direction, that is, the direction of wind as seen by the ship.

1. Sliding Contactors.

a. Sliding Contactor Attached to Pennant.

A contact slider arm, shown in fig.1., is rigidly attached to the shaft on which the pennant is mounted. As the wind direction shifts, the pennant, its shaft, and the contact slider arm are rotated, much the same as a weather vane is rotated. The contact arm is made to slide along a circular coil of resistance wire. This resistance forms one branch of a Wheatstone bridge circuit, see fig.3. The value of this resistance, which is shown in the bridge circuit from "a" to "b" in figures 1 and 3, varies with changes in direction of

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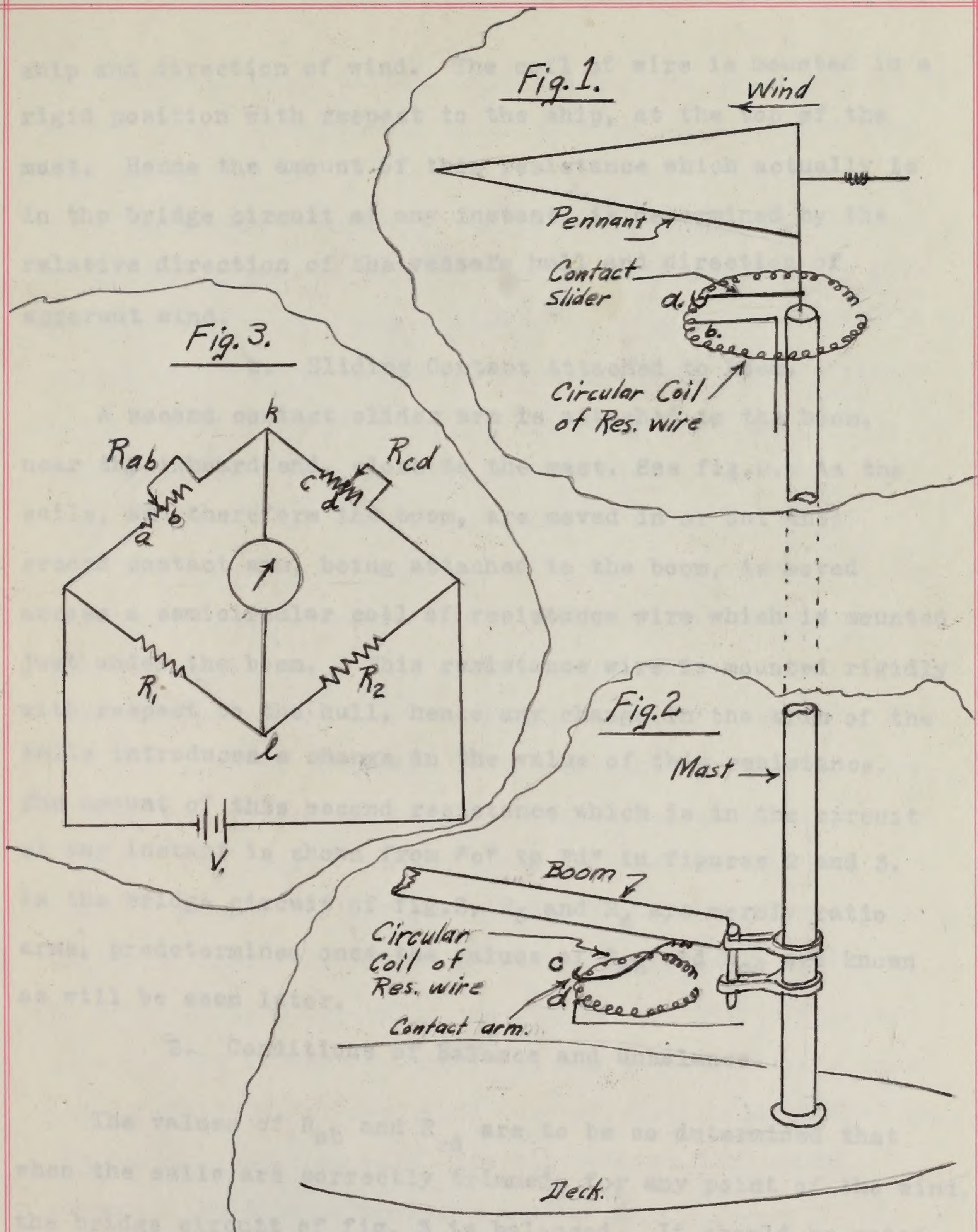


Fig. 1.
Wind
Pennant
Contact
Slider
d.
b.
Circular Coil
of Res. wire
Fig. 3.
k
Rab
Rcd
c
d
b
a
R1
R2
l
V.
Fig. 2
Mast
Boom
Circular
Coil of
Res. wire
c
d
Contact arm.
Deck.

ship and direction of wind. The coil of wire is mounted in a rigid position with respect to the ship, at the top of the mast. Hence the amount of this resistance which actually is in the bridge circuit at any instant, is determined by the relative direction of the vessel's hull and direction of apparent wind.

b. Sliding Contact Attached to Boom.

A second contact slider arm is attached to the boom, near the inboard end, close to the mast. See fig.2. As the sails, and therefore the boom, are moved in or out this second contact arm, being attached to the boom, is moved across a semicircular coil of resistance wire which is mounted just under the boom. This resistance wire is mounted rigidly with respect to the hull, hence any change in the trim of the sails introduced a change in the value of this resistance. The amount of this second resistance which is in the circuit at any instant is shown from "c" to "d" in figures 2 and 3. In the bridge circuit of fig.3, R_3 and R_4 are merely ratio arms, predetermined once the values of R_{ab} and R_{cd} are known as will be seen later.

2. Conditions of Balance and Unbalance.

The values of R_{ab} and R_{cd} are to be so determined that when the sails are correctly trimmed, for any point of the wind, the bridge circuit of fig. 3 is balanced. It should be noted

here that the angle between wind and sail is not constant, but varies from a minimum when pointing high, to a maximum when running free.

Resistors R_{ab} and R_{cd} are to be so determined that if the sails are trimmed either too flat or too free, for any given point of the wind, the resistance R_{cd} ,fig.2, likewise will be either too large or too small in comparison with resistance R_{ab} and balanced conditions in the bridge will not exist. This could be indicated by a galvanometer if one were placed between "k" and "l" as shown in fig.3.

Now consider balanced conditions. This means that the sails are trimmed correctly for the prevailing wind. The wind is striking the sail at the correct angle. There is no current through the galvanometer branch of the bridge. Now consider a shift in wind. If the ship remains on the same course, and if the set of the sails is not changed, the resistor R_{ab} , figs, 1 and 3, being dependent on the angle between pennant and hull, will change without a corresponding change in R_{cd}, figs. 2 and 3, which is dependent on the angle between the boom and hull. Unbalanced conditions will now exist in the bridge circuit until the resistor at the boom can be adjusted for new conditions of equilibrium, (that is, the sails reset), or until the wind shifts back again, assuming the course to remain unaltered.

The wind can not be depended upon to shift back to the direction which previously gave balanced conditions. Therefore the sails either should be pulled in or let out until the angle between the wind and the sails is again correct for good driving power. New conditions of balance will now exist in the bridge. Note here that: 1) The resistor at the pennant is a measure of the angle between the apparent wind and the hull. 2) The resistor at the boom is a measure of the angle between the boom and the hull. 3) The resistor at the boom may be considered as a dependent variable, its value being determined by the set of the sails, depending on the value of the resistor at the pennant. The resistor at the pennant, on the other hand, may be considered as an independent variable, since its value is subject only to the fancies of Mother Nature. 4) At unbalanced conditions the current may flow in either direction through the galvanometer circuit depending on whether R_{ab} is greater or less than R_{cd}. This reversibility is important since it gives an indication of whether a wind ~~may~~ shift may be foreward or aft. 5) Under balanced conditions there is no current flow through the galvanometer circuit.

Consider the bridge of fig.3, and replace the galvanometer by a relay control device to operate a motor, as shown in fig.4. The motor in turn operates the trim of the sails.
If unbalanced conditions exist a direct current flows through the relay unit (connected where the galvanometer would be for

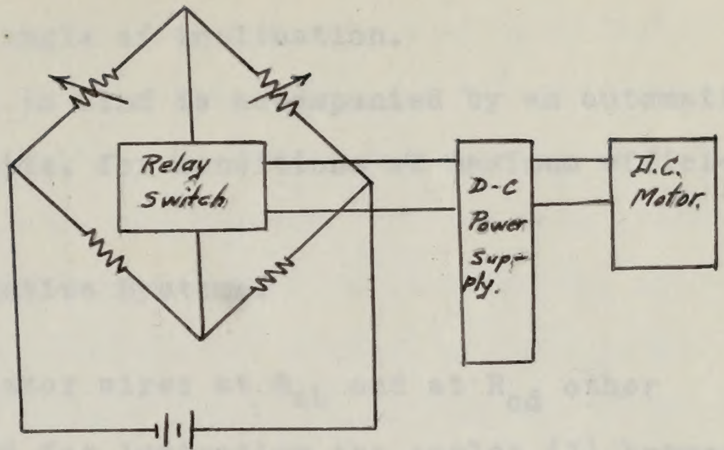


Fig. 4.

the usual Wheatstone bridge) in one direction or the other. The relay controls the motor, causing rotation in one direction or the other, depending on the direction of the direct current through the relay activating it. The motor in turn either pulls in or lets out the sail. The sail is attached to the boom, and the boom is attached to the contact slider arm at R_{cd}. Hence any change in the trim of the sail will introduce a change in the value of R_{cd} in the bridge circuit.

As long as unbalanced conditions exist, a direct current continues to flow through the relay; which continues to operate the motor; which continues to adjust the sail; which is attached to the boom; thereby continuing to change R_{cd} until new balanced conditions exist. At this new balance there will be no direct current through the relay, the motor will cease to operate, and also the wind will be striking the

sail at the correct angle of inclination.

Hence any shift in wind is accompanied by an automatic adjustment of the sails, for conditions of maximum efficiency and driving power.

3. Alternative Systems.

Instead of resistor wires at R_{ab} and at R_{cd} other methods might be used for indicating the angles (1) between apparent wind and hull, and (2) between sail(or boom) and hull. By "hull" is meant the longitudinal fore-and-aft axis of the hull, that is, the line of the keel.

One method would be to use enclosed light sources. polarized filters, and photoelectric cells, in place of R_{ab} and R_{cd}. As the pennant shifts, or as the boom is moved, the amount of light permitted to pass through the polaroid filter from the lamp to the corresponding photocell would be varied.

Another method would be to make use of servo-mechanisms. The problems involved using resistors in the bridge circuits, however, will be discussed in detail here.

B. Angles Between Apparent Wind (Pennant) and Sail.

1. Variables.

In this section the requirements for correlating the resistance at the pennant with the resistance at the boom are discussed. Correlation of resistances at boom and at pennant for balanced conditions means that there is no current flow through the relay of fig.4, and that the motor is not operating.

Balanced conditions are the desired operating conditions. They are striven for at all times. For any fluctuations in wind direction producing unbalance, the motor adjusts the sail until balance is re-obtained. It has been stated that at balanced conditions the wind is striking the sails at the correct angle. What is the correct angle? Is it a constant value for various points of sailing, or is it a variable?

The correct angle of wind with sail is not a constant. It varies with point of sailing, going from a minimum when pointing high, to a maximum when running free. Furthermore, the angle between wind and sail varies for individual sails, depending on the shape of sail profile, and on the depth and location of the belly of the sail. The profile is seen when looking at the sail side view. The belly refers to the deviation from a straight line as seen when considering a cross section of the sail, looking down from above, the sail being filled with wind.

Now for the purpose of explanation, a typical case will be first used where the angles of inclination of wind to sail vary from a minimum of ten degrees to a maximum of ninety degrees, depending on the point of sailing.

2. Fundamental Principles of Sailing.

Before proceeding further a brief description of the fundamental principles of sailing will be given.

Refer to fig.5. The wind strikes the sail at an angle. The force on the sail is normal to the surface of the sail cloth, neglecting the small force of friction parallel to the sail.

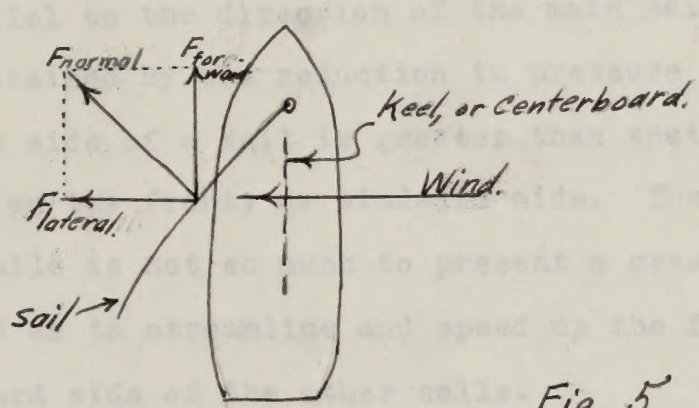


Fig. 5.

This force has two components, a forward, and a sideward component. The forward component is useful in driving the ship ahead.The sideward component represents wasted energy, actually energy detrimental to the distance made good, since it does not help the ship ahead any, but represents a sideslip which must be made up for, by travelling a longer distance. A keel, or a centerboard built parallel to the fore-

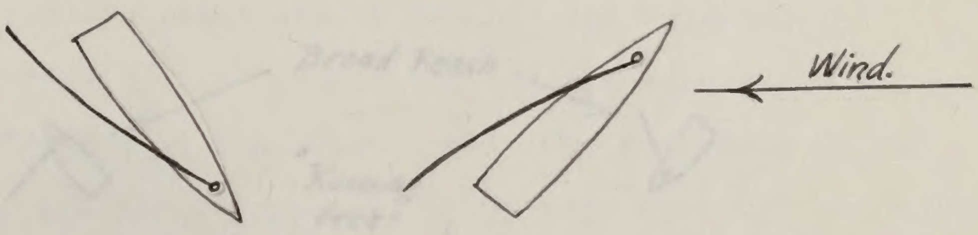


Fig. 6.

and-aft axis of the hull represents a lateral surface to the water to prevent excessive sideslip due to the sideward component of force on the sail. In general if there is more than one sail on a ship the additional sails are more or less maintained parallel to the direction of the main sail. The driving force obtained by the reduction in pressure on the leeward, or back side of a sail is greater than that obtained by the pressure on the front, or windward side. The purpose of additional sails is not so much to present a greater sail area to the wind as to streamline and speed up the flow of air on the leeward side of the other sails.

Figures 6 and 7 show the correct positions of sail for

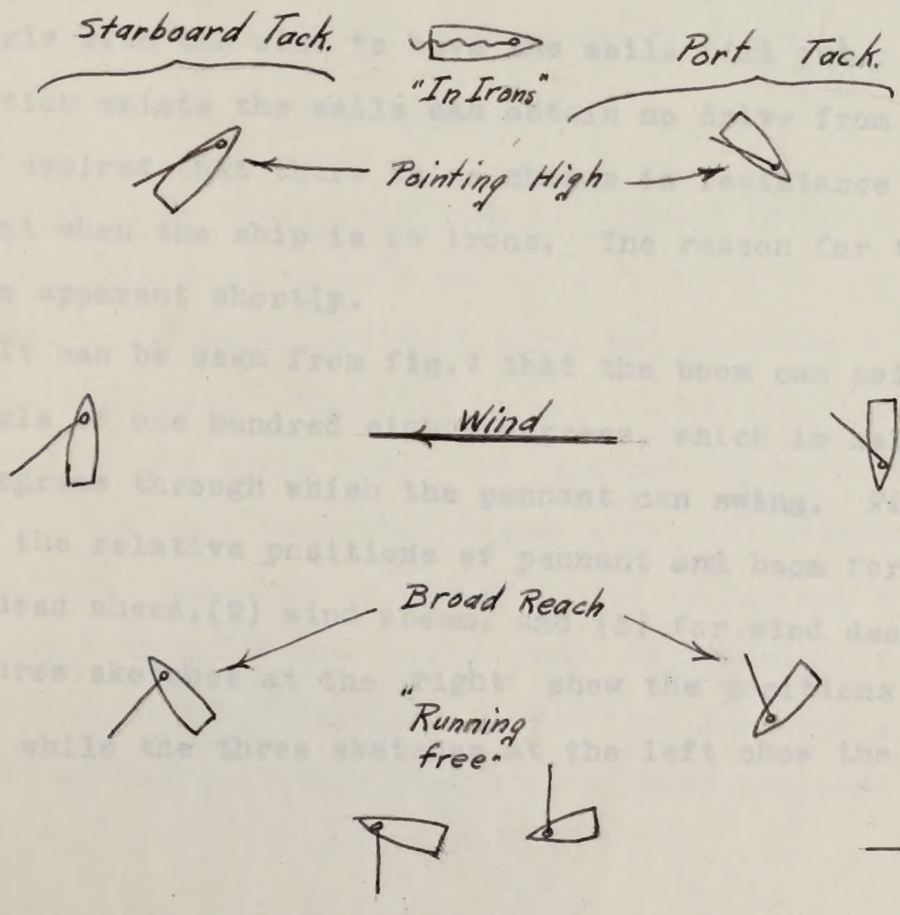


Fig. 7.

the various points of sailing. Figure 7 follows a ship through 360 degrees rotation.

3. Angles Through Which Pennant and Boom Swing.

The pennant on top of the mast must be allowed to move through 360 degrees with no mechanical stop to prevent it from rotating in any direction that the wind blowsit. This is seen from fig.7.

It will be noticed that there is a "dead angle", when the ship is heading practically into the wind. In this position the ship is said to be "in irons". In this position the ship is either directly into the wind, or at too small an angle with the wind to have the sails fill out. When this condition exists the sails can obtain no drive from the wind. It is desired that there be no change in resistance at the pennant when the ship is in irons. The reason for this will become apparent shortly.

It can be seen from fig.7 that the boom can swing through an angle of one hundred eighty degrees, which is half of the 360 degrees through which the pennant can swing. Figure 8 shows the relative positions of pennant and boom for (1) wind dead ahead,(2) wind abeam, and (3) for wind dead astern. The three sketches at the right show the positions of the boom, while the three sketches at the left show the correspond-

ing positions of the pennant's contact slider arm, for these wind directions.

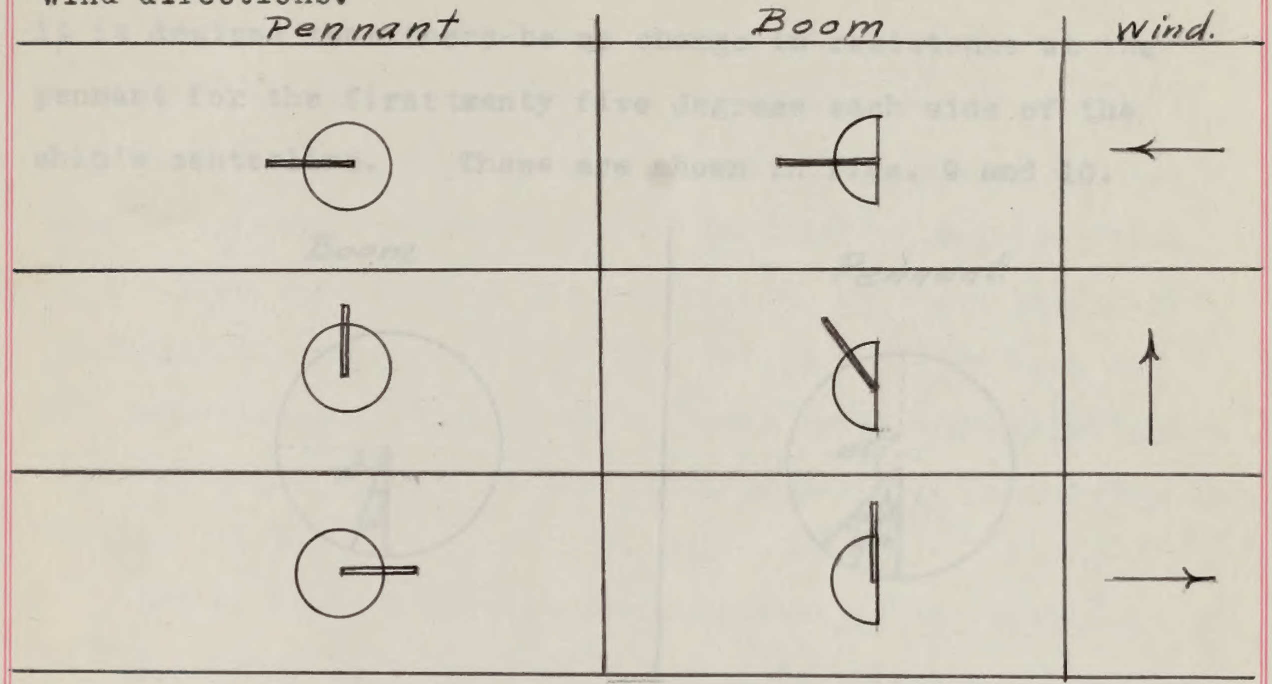


Fig. 8.

a. Close Hauled.

When close hauled the boom is trimmed in to an angle of about fifteen degrees with the line of the keel. Some ships can trim booms in closer than this, but this value is selected to work with here. The boom is not trimmed all the way in parallel to the keel, because a forward component of the force on the sail is needed to drive the ship ahead. It is desired that there be no change in the resistance at the boom throughout this fifteen degree swing either side of the hull's centerline. It is likewise desired that the wind strike the sail at an angle of about ten degrees when the sail is close

hauled. Thus the angle between the wind and the hull will be the sum of these two, or twenty five degrees. Accordingly it is desired that there be no change in resistance at the pennant for the first twenty five degrees each side of the ship's centerline. These are shown in figs. 9 and 10.

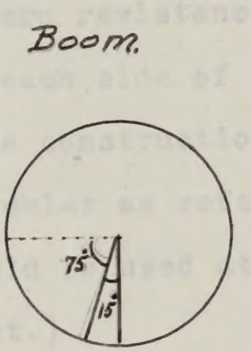


Fig. 9.

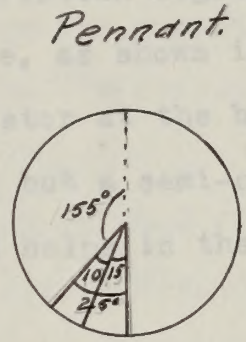


Fig. 10.

Let R_p represent the resistance at the pennant, and R_b represent the resistance at the boom. At balanced conditions, $\frac{R_P}{R_B} = \frac{R_1}{R_2}$

$$R_P = \frac{R_1}{R_2} \times R_B.$$

Due to unbalance of the bridge:

If $R_p > R_b\ (R_1/R_2)$ the sail is automatically let out.

If $R_p < R_b\ (R_1/R_2)$ the sail is automatically pulled in.

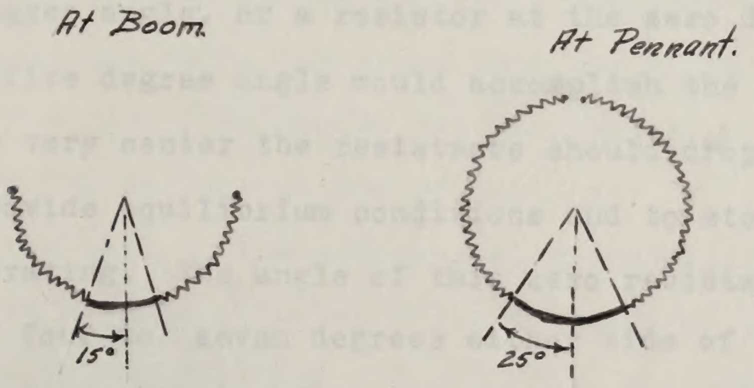
Reference to figure 11, showing the resistor wires at the pennant and at the boom will help to visualize this.

In other words, any change in the resistance in the bridge circuit

at the pennant is "followed up" by a corresponding change in the resistance in the bridge circuit at the boom.

The resistor at the pennant is so constructed that the twenty-five degrees each side of the centerline shown in figure 11 is of zero resistance. Also the resistor at the boom is of zero resistance during the fifteen degrees swing of the boom each side of the centerline, as shown in fig.11 (Actually the construction of the resistor at the boom is not semi-circular as referred to here; but a semi-circular resistor could be used at the boom,and helps in the explanation at this point.)

Now if a short circuit(zero resistance) is obtained at the pennant it means that the ship is in irons. Thus the boom should be trimmed all the way in to any angle within fifteen degrees of the centerline. Therefore the resistance at the boom is selected to be constructed equal to zero for this fifteen degrees each side of the centerline.



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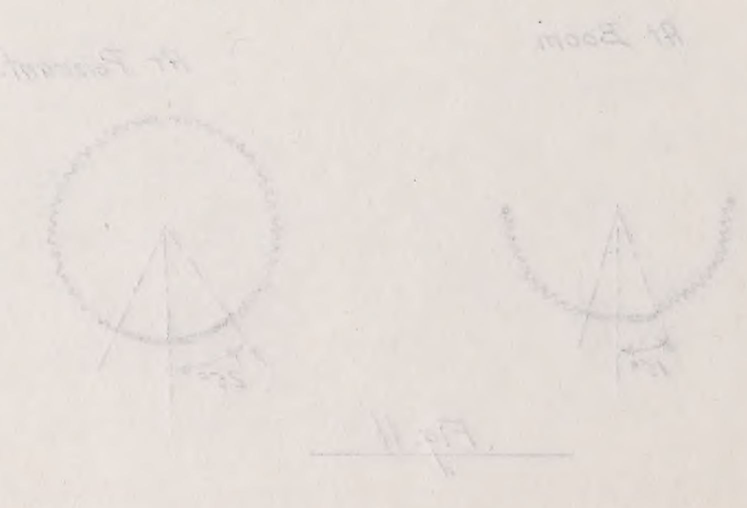

Fig. 11

When the ship falls into irons the sail will remain trimmed in tight, until the ship swings enough to have the wind strike the sails at an angle of ten degrees or more upon which some resistance will be inserted in the circuit at the pennant. Only after some resistance has been added at the pennant will the boom "follow up" and allow some resistance to be added in the circuit from the resistor at the boom by means of the boom's swinging out. The force causing the boom to swing out is derived from the wind in the sails.

If it were desired to have the boom trimmed flat, that is, all the way in, instead of just to within fifteen degrees of the hull, then the resistance at the boom would not be constructed equal to zero throughout this twenty-five degree angle on either side of the hull's centerline. Some resistance left in would insure the boom's being trimmed in tight whenever the pennant resistance dropped to zero. The resistance at the boom would try to "follow up" the change in resistance at the pennant.

Either a uniform resistor wire here at the boom for the twenty-five degree angle, or a resistor at the zero degree end of the twenty-five degree angle would accomplish the same results. At the very center the resistance should drop to zero in order to provide equilibrium conditions and to stop the motor from operating. The angle of this zero resistance will be around four to seven degrees either side of zero due to the impracticability of trying to trim the sail any

closer than this.

b. Increase of Angles as Ship Falls Off.

Now, the angle between wind and sail was set at ten degrees when close hauled. If the next 75 degrees swing of boom introduces a resistance equal to the resistance introduced by the next 155 degrees sweing of the pennant, then balanced conditions will exist in the bridge circuit with the wind inclined to the sail at an angle which increases uniformly from ten degrees to ninety degrees as the point of sailing shifts all the way from pointing high to running free. This means that the resistance per unit angle of R_b is 155/75 times R_p per unit angle. Or in a more straightforeward arrangement, the resistances of the resistors at the pennant and at the boom would be equal, introducing equal resistances into the circuit for equal angles of swing, and the ratio arms shown in fig.3, would be such that: $R_1/R_2 = 155/75$.

Now it so happens that the change of angle of inclination of wind onto sail does not follow a linear relationship to the angle between wind and hull. By experience the skipper of a ship finds out what angle he should set his sail at for the best results for the various points of sailing.

It would be a tedious and unnecessarily complicated job to tabulate a set of data obtained while sailing, of the angles between wind and hull for all points of sailing, which would give the best results, unless some neat arrangement could

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be used to mechanize the procedure of taking data.

4. Method of Obtaining "Cam" Calibration data.

It has been stated that the calibration, that is, the variation between wind and sail for the various points of sailing differ for each ship and from sail to sail. Hence each sail used on a given ship will require its own calibration. Once a sail has been "calibrated" a cam may be laid out for that sail. The shape of the cam is a function of the calibration of the sail. The cam is attached to the boom, in place of what has formerly been thought of as a contact slider arm attached to the boom. The resistor at the boom is actually constructed so that it forms a straight coil, and a slider can move back and forth along it. The slider is controled by the shape of the cam. Hence the resistor at the boom may be constructed of uniform resistance per unit length, but a non-uniform amount of resistance from this resistor inserted into the circuit for uniform angles of swing of the boom.. This is accomplished by virtue of the cam's having a non-circular shape, actually a shape that departs from circular in a non uniform manner, depending on the calibration of the sail.

Each sail may have its own cam. Therefore when sails on a ship are changed, the cam is changed also, and the ship is enabled to sail efficiently with the new sail.

All the other control equipment can be used interchangeably from one sail to another.

This calibration by shape of a cam is more straightforeward than calibration by means of varying the spacings between the individual coiled wire turns at the pennant and at the boom.

A suggested procedure for the process of obtaining data for the calibration of a sail follows. A convenient method, eliminating much of the labor and human errors in taking calibration data of a sail would be to obtain readings photographically. The equipment required would consist of a camera(miniature would be sufficient), an instrument with dial calibrated to indicate the angle between apparent wind and hull (pennant), and a second instrument to indicate the angle between the sail and the hull. The procedure then would be to take the ship out and actually sail her. When the skipper has adjusted the sails for the best efficiency, to the best of his ability, and the ship appears to be sailing at maximum speed for the given point of sailing, the camera shutter is tripped. A simultaneous picture is taken of the two required readings, by photographing the two instruments. The direction of the ship is then changed through any angle, (not in irons) and the sails are again adjusted for best operating conditions. The camera shutter is again tripped, giving another set of data.

This process is repeated, taking photographs for all

points of sailing. The larger the number of pictures taken the closer the average will be to the actual best values.

Note that the pictures need not be taken in any chrono-logical manner, that is, successive pictures need not be for small continuous changes in direction of point of sailing. All points of data will take their proper place when plotted. This further eases the work of calibration. Any set of angles may be photographed when best sailing conditions are obtained.

After the photographs have peen processed, the results may be plotted, showing the angle between wind and hull as

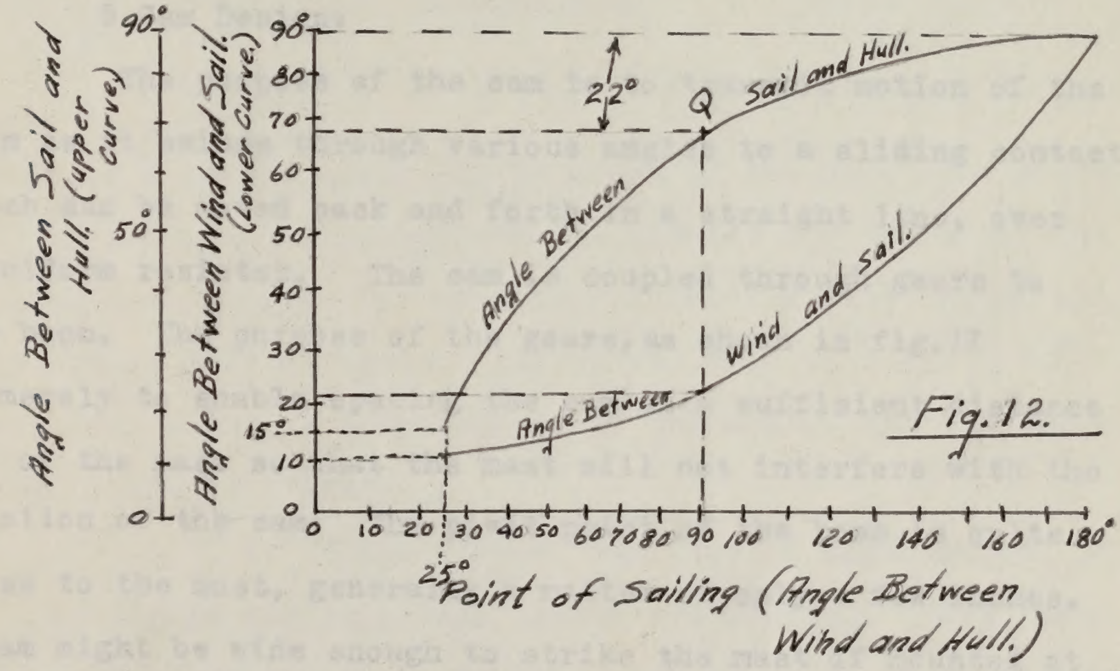

Fig. 12.

abscissa (point of sailing, as indicated by the pennant), versus the angle of inclination of wind onto sail as ordinates. See fig.12.

The angle between wind and sail is obtained by subtracting the angle between sail and hull from the angle between wind

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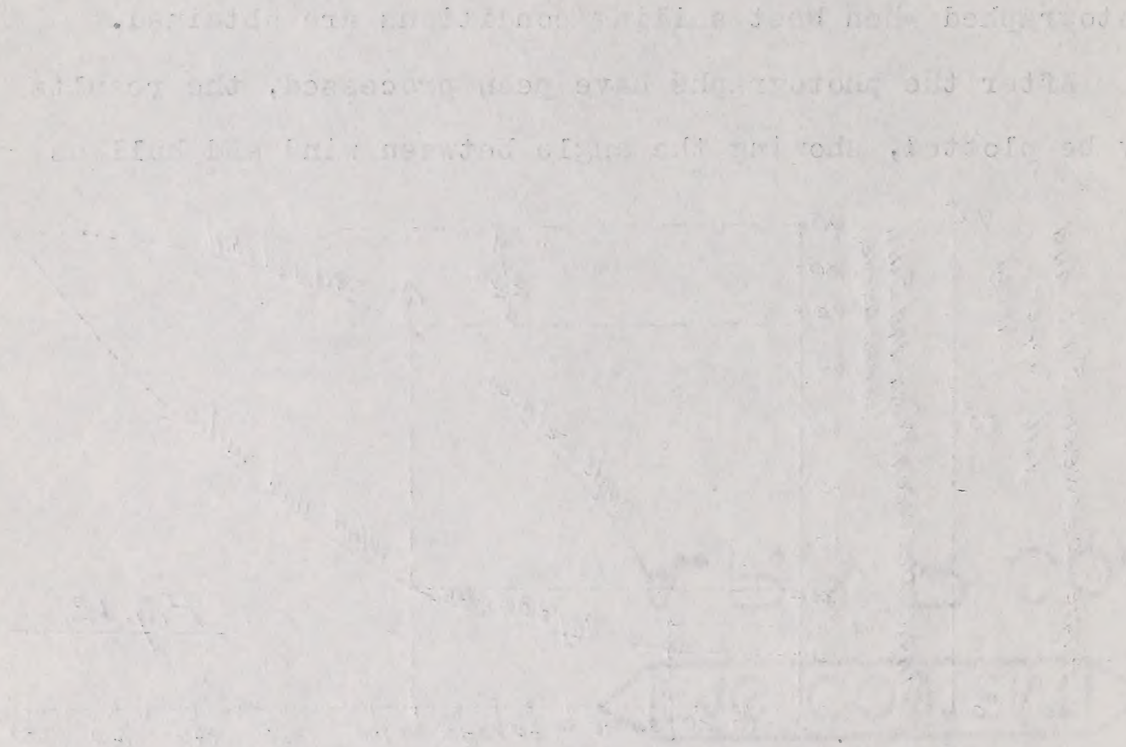

direction (point of sailing, as indicated by the pennant), versus the angle of inclination of [illegible]. See fig.17.

The angle between wind and sail is obtained by subtracting the angle between sail and hull from the angle between wind

and hull.

After all the points have been plotted, a smooth curve may be drawn through the averages of these points. This is now a calibration curve for the best operating conditions for the particular sail and ship for all points of sailing . Note that the points will be the same for both the port and starboard tacks, hence only the points for one tack need be plotted. However, the cam must be operative for both the tacks and is designed symmetrically, using values from the plot for both halves, as will be seen.

5.Cam Design.

The purpose of the cam is to transmit motion of the boom as it swings through various angles to a sliding contact which can be moved back and forth in a straight line, over a uniform resistor. The cam is coupled through gears to the boom. The purpose of the gears, as shown in fig.17 is merely to enable spacing the cam at a sufficient distance aft of the mast so that the mast will not interfere with the rotation of the cam. The pivot point of the boom is quite close to the mast, generally a matter of only a few inches. A cam might be wide enough to strike the mast if mounted at the pivot point of the boom, when the boom is swung out at large angles with the hull. However, the cam rotated by the boom, passes through the identical angles that the boom passes through. That is, the rotation of the cam is not a multiple

or a sub-multiple of the rotation of the boom.

If the cam were semi-circular in shape, there would be no motion of the sliding contact, P, of fig.13.

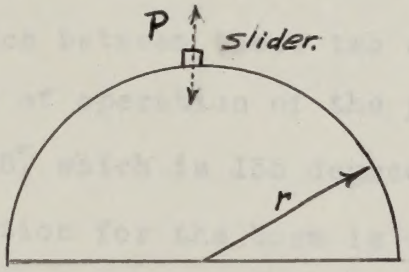

Fig. 13.

Motion of P is dependent on the shape of the cam. The greater the change from a circular cam the greater the motion of the sliding contact, P. For example, if the cam were in the shape of a logarithmic or equiangular spiral $\rho = e^{a\theta}$, or $\log \rho = a\theta$, the radius would be proportional to the angle, and the slider motion would be linear.

a. Shape of Cam from Plot of Experimental Data.

In fig.12 two important curves are plotted. Note that the ordinate of any point on the curve of inclination angle of wind onto sail, versus point of sailing is equal to the abscissa minus the corresponding ordinate of the curve for the angle between the sail and the hull, versus "point" of sailing curve. In obtaining the photographic data the angle between wind and hull was measured, and the angle between sail(or

boom) and hull was also measured. (The indications noted on ammeters can be a function of resistances cut in and out at the boom and at the pennant as the wind shifts and as the sails are shifted.) Now the angle between the wind and the sail is the difference between these two angles.

The total angle of operation of the pennant (on each tack) equals 180° - 25°, which is 155 degrees of swing, The total angle of operation for the boom is 90° - 15°, which is 75 degrees of swing(for each tack). This is seen on fig. 12 also.

To investigate the relationships between these angles between wind, sail, and hull when the wind is abeam refer to fig.12. With the wind abeam, the point of sailing is 90 degrees. The corresponding angle between sail and hull was found to be 68 degrees. The difference between the two is 22 degrees, which is the angle of inclination of wind onto sail for a typical modern sail with the wind abeam.

Now, to obtain balanced conditions for any point of sailing, the same percentage of the total resistance of each resistor(at the pennant, and at the boom) must be in the circuit at any time. To investigate cam design consider these percentages when the wind is abeam, referring to fig.14.

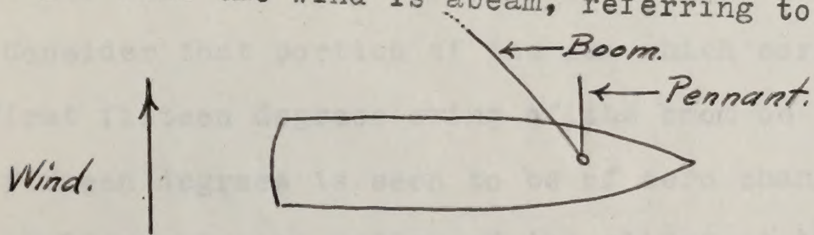

Fig. 14.

$$\frac{(90-25)}{(180-25)} \times 100 =$$ percentage of total resistance in the circuit at the pennant, with the wind abeam.

Making a general case, by substituting Q_p in place of 90 degrees for angle between wind and hull, gives:

$$\frac{(Q_P-25)}{(180-25)} \times 100 =$$ percentage of total resistance in the circuit at the pennant, on any point of sailing.

To find the percentage of the total resistance at the boom which is in the circuit with the wind abeam, recalling that the sail is let out from the hull an angle of 68 degrees with the wind abeam gives:

$$\frac{(68-15)}{(90-15)} \times 100 =$$ percentage of total resistance in the circuit at the boom, with the wind abeam.

Making a general case, by substituting Q_b in place of 68 degrees for the angle between boom and hull, gives:

$$\frac{(Q_B-15)}{(90-15)} \times 100 =$$ percentage of total resistance in the circuit at the boom, on any point of sailing.

Consider that portion of the cam which corresponds to the first fifteen degrees swing of the boom on each tack. This fifteen degrees is seen to be of zero change in resistance. This would require no motion of the slider at the resistor

at the boom. However, it would be well to design the cam so that it will give some motion to the slider for angles of less than fifteen degrees. This will get the contact slider away, and entirely clear from the resistance at R_b for these angles, and will move the slider onto wire of virtually zero resistance. Thus stable conditions are insured causing no operation of the motor in this angle. If the radius of the cam were a constant through this fifteen degree angle the slider would not be in a fool-proof location, but might conceivably be allowed to come in contact with some resistance , allowing some resistance to be in the circuit at R_b. The unit would be continually at the dividing line between being operative, and being balanced(no operation of motor). The shape of the cam in this region need not be held to close limits. Just as long as the slider is moved clearly into the zero resistance section of R_b the cam has done its job at these angles.

To calculate the shape of the cam, the radii of the cam corresponding to the angles on the cam can be found. For any angle of swing of the pennant(angle between wind and hull) the required angle of swing of boom is known from the curve of fig.12.

The known factors may be listed as:

1) The angle of boom for any angle of pennant, is found from figure 12, as a result of the photographic calibration data.

2) Calculation of percentage of pennant's working angle, and calculation of percentage of boom's working angle, at any point of sailing,

at the boom. However it would be well to design the cam so that it will give some motion to the slider for angles of less than fifteen degrees. This will get the contact slider away, and entirely clear from the resistance at R_b for these angles, and will move the slider onto wire of virtually zero resistance. Thus stable conditions are insured causing no operation of the motor in this angle. If the radius of the cam were a constant through this fifteen degree angle the slider would not be in a fool-proof location, but might conceivably be allowed to come in contact with some resistance, allowing some resistance to be in the circuit at R_b. The unit would be continually at the dividing line between being operative, and being balanced(no operation of motor). The shape of the cam in this region need not be held to close limits. Just as long as the slider is moved clearly into the zero resistance section of R_b the cam has done its job at these angles.

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The known factors may be listed as:

1) The angle of boom for any angle of pennant, is found from figure 12, as a result of the photographic calibration data.

2) Calculation of percentage of pennant's working angle, and calculation of percentage of boom's working angle, at any point of sailing,

using previous sample calculations, pg. 29.

3) The percentage of the total resistance at the pennant, which is in the circuit at any instant, is equal to the percentage of the total working angle at the pennant.

4) The percentage of the total resistance at the boom, which is in the circuit at any instant, is not equal to the percentage of the total working angle at the boom.

But, 5) The percentage of the total resistance at the boom must equal the percentage of the total resistance in at the pennant, in order to obtain balanced conditions.

Therefore, 6) $$\left(\frac{Q_B - 15}{90 - 15}\right) \times S = \left(\frac{Q_P - 25}{180 - 25}\right)$$

Where S is the percentage of the total resistance in the circuit at the boom.

For any cam angle, from 0 to 90 degrees, (not from 15 to 90 degrees) the percentage of the total R_b in the circuit is equal to the same percentage of the total R_p which is in the circuit. Hence for any point Q the percentage of the resistance in the circuit found on the abscissa from $\left(\frac{Q_P - 25}{180 - 25}\right) \times 100$, is also the percentage of the total R_b that is to be in the circuit for angle of boom at Q_b. This percentage, S, of the total R_b is the percentage of maximum change in the radius of the cam. The cam may now be laid out as shown in fig.15.

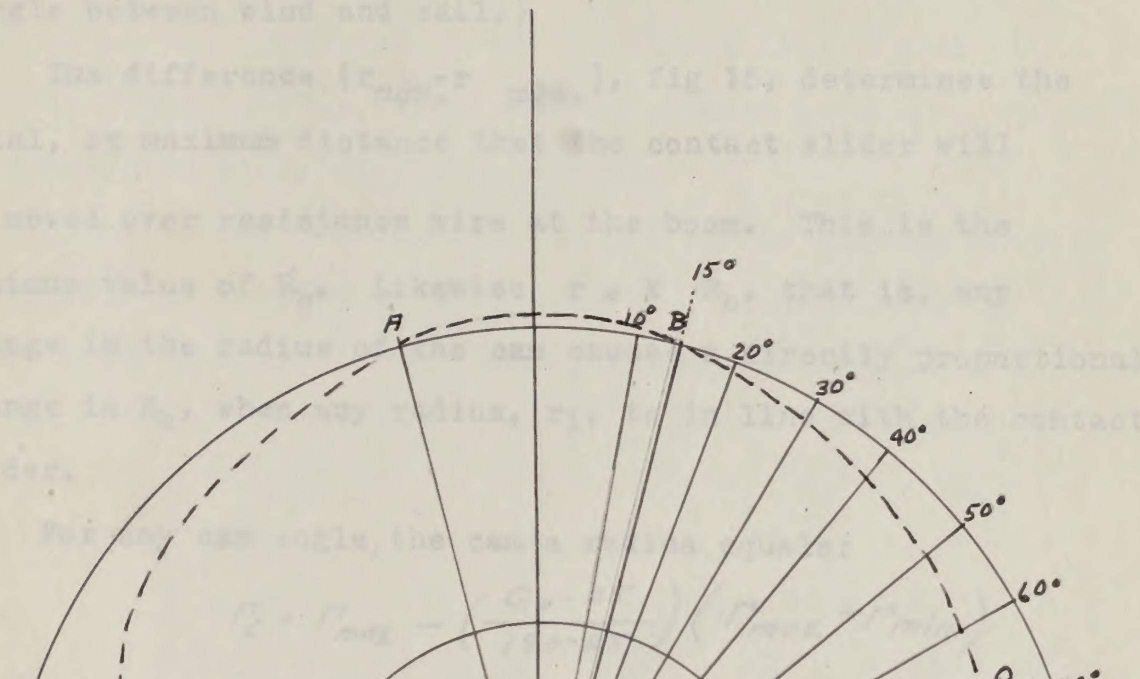


Fig. 15.

For each half of the cam the angles shown on the cam in fig. 15 correspond to the angles plotted as ordinates in fig 16. (angle between wind and sail.)

The difference ($r_{max.}$-$r_{min.}$), fig 15, determines the total, or maximum distance that the contact slider will be moved over resistance wire at the boom. This is the maximum value of R_b. Likewise $r = k\ R_b$, that is, any change in the radius of the cam causes a directly proportional change in R_b, when any radius, r_i, is in line with the contact slider.

For any cam angle, the cam's radius equals:

$$r_i = r_{max.} - \left(\frac{Q_P - 25}{180-25}\right)\left(r_{max.} - r_{min.}\right)$$

In the second term on the right hand side of the equation, $\left(\frac{Q_P - 25}{180-25}\right)$ is the fraction of the total R_b, $R_b = k(r_{max.} - r_{min.})$ to be added to the minimum radius ($r_{min.}$) for any cam angle.

As an example to illustrate this, and to predict the general shape of the cam, consider the case of the wind abeam, for a triangular sail. With wind abeam, the angle between apparent wind and hull is 90 degrees. A typical angle between sail and hull (also referred to as cam angle) is 68 degrees. Thus the wind is inclined to the sail at an angle of 22 degrees. (90-68=22).

From fig.12:

$$\Delta r_{90} = \frac{Q_P - 25}{180-25} \times 100 = \frac{90-25}{180-25} \times 100 = \frac{65}{155} \times 100 = 41.9\%$$

This corresponds to a cam angle of 68 degrees. The significance of the shape of the cam as predicted by this one point, with wind abeam can more readily be visualized from a plot of cartesian coordinates, than when first seen on a cam. Therefore, the following plot, fig16, is presented.

In cartesian coordinates the plot of Percent of Maximum Resistance in circuti at R_b versus the Cam Angle, or the Angle Between Boom and Hull would appear as follows:

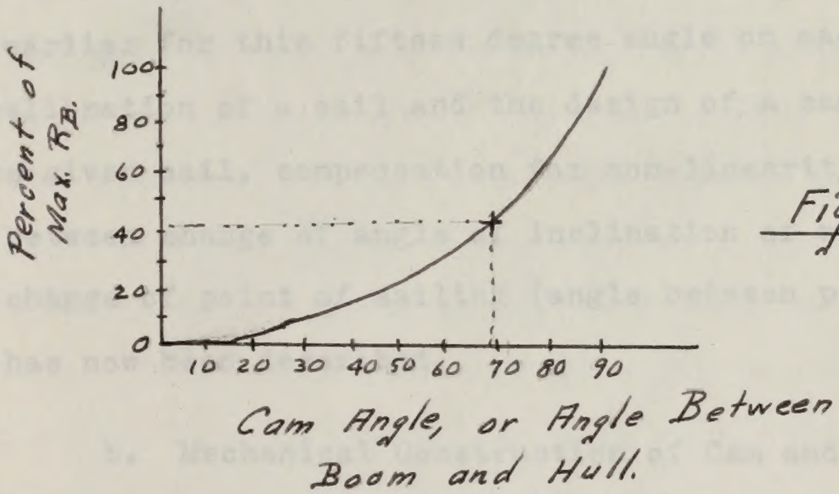


Fig. 16.

It will be noticed that the slope of the above curve is small to start with, and increases gradually. It increases slowly at first, and quite rapidly for the larger Cam Angles. This is another way of saying that the change in angle of inclination of wind into sail is small when pointing high, and as wind hauls aft, increases slowly for winds before the beam, and rapidly for winds abaft the beam.

The fact that no resistance is introduced at R_b for the first fifteen degrees on each tack is also seen on this curve.

Where the slope of the curve is small the sail has to move through a large angle to introduce the same change in R_b, as compared with the angle the sail has to move through when the slope of curve fig,16 is greater.

It will be noticed that the radius of the cam, fig.15, between the points "A" and "B" on the periphery has been increased to exceed the r_{max}. The reason for this is to move the sliding contact clear of the resistance portion of the wire , and onto the "zero resistance" portion of R_b, as mentioned earlier for this fifteen degree angle on each tack.

The calibration of a sail and the design of a cam to go with the given sail, compensation for non-linearity of the ratio between change of angle of inclination of wind onto sail, and change of point of sailing (angle between pennant and hull) has now been described.

b. Mechanical Construction of Cam and Cam Assembly.

The mechanical construction of the cam should be such that it present a hard, smooth surface to the sliding contact. The cam should be rugged enough so that it will not warp or loose its shape. Duraluminum, aluminum, or brass plate, one-eighth to one-half inch thick are good materials to use in construction of the cam.

The size of the cam is determined by the length of the

resistor used at R_b. The longer this resistor, and the larger the cam the greater the accuracy that can be expected. A cam might have a maximum radius in the neighborhood of three inches for a six-foot model yacht, or a foot for a full sized ship.

The following drawings show the construction of the equipment described. Figure 17 shows:the layout of cam, resistor R_b, contact slider at boom, gears for spacing the cam away from the mast, the coupling of the gears to the gooseneck, and also the boom and the mast. Fig.17 also shows both top view and side view of this equipment.

It can be seen from figure 17 that the contact slider is actuated by the cam. However, there is a coil spring which is compressed at all times, on the other side of the contact slider. This compressed coil spring serves to keep the contact slider up snug against the edge of the cam at all times.

It will be noted that in the central position of the boom and cam, the contact slider has been mooved away from the resistive part of R_b and is making contact with the zero resistance part of R_b.

The top view brings out the fact that the cam would strike the mast when the boom and the cam were swung out through a 90 degree angle if the cam were not spaced aft from the mast by the gears.

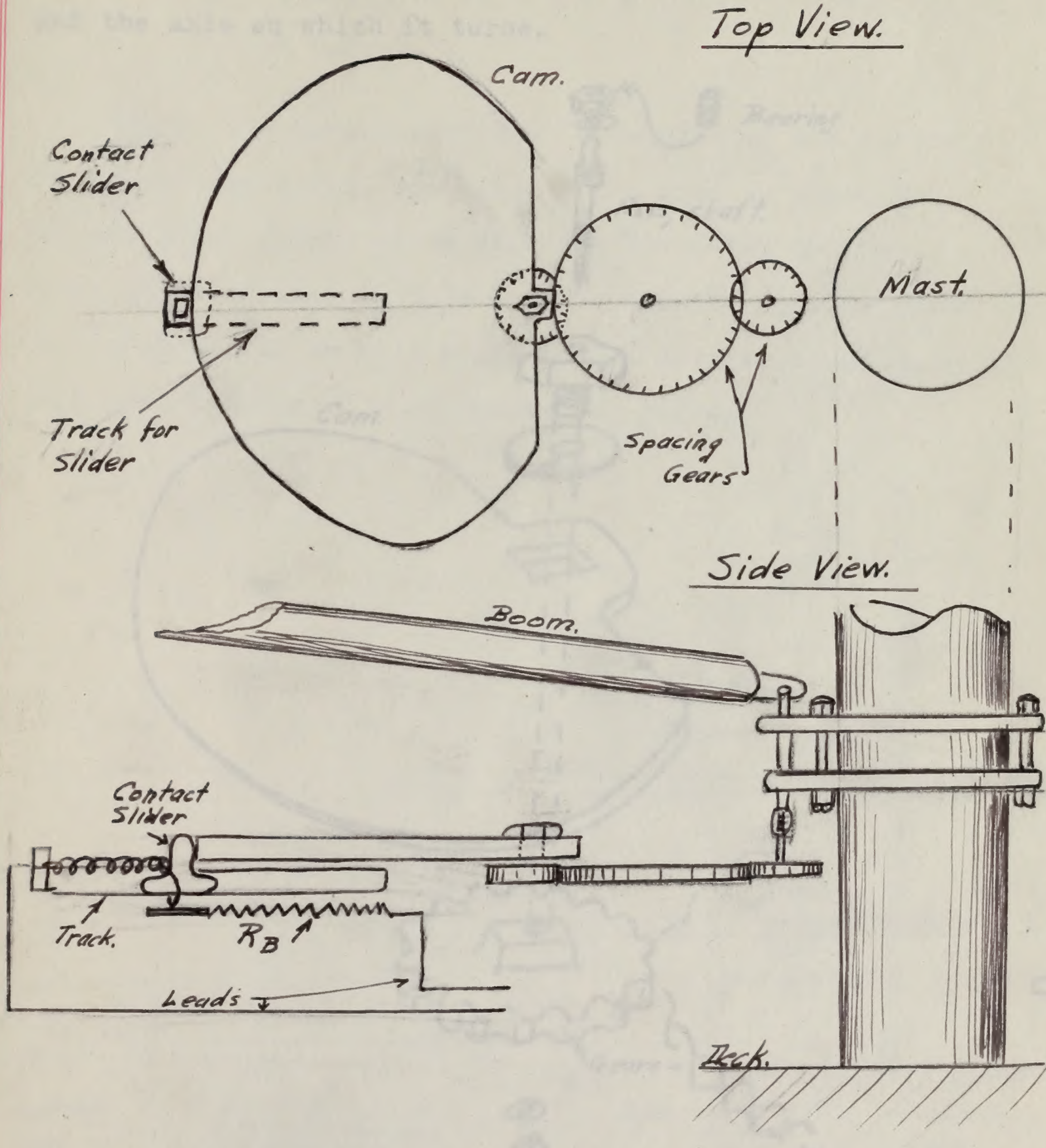

Top View.
Cam.
Contact Slider
Track for Slider
Mast.
Spacing Gears
Side View.
Boom.
Contact Slider
Track.
R_B
Leads
Deck.

Fig. 17.

Figure 18, shown below, shows the assembly of the cam and the axis on which it turns.

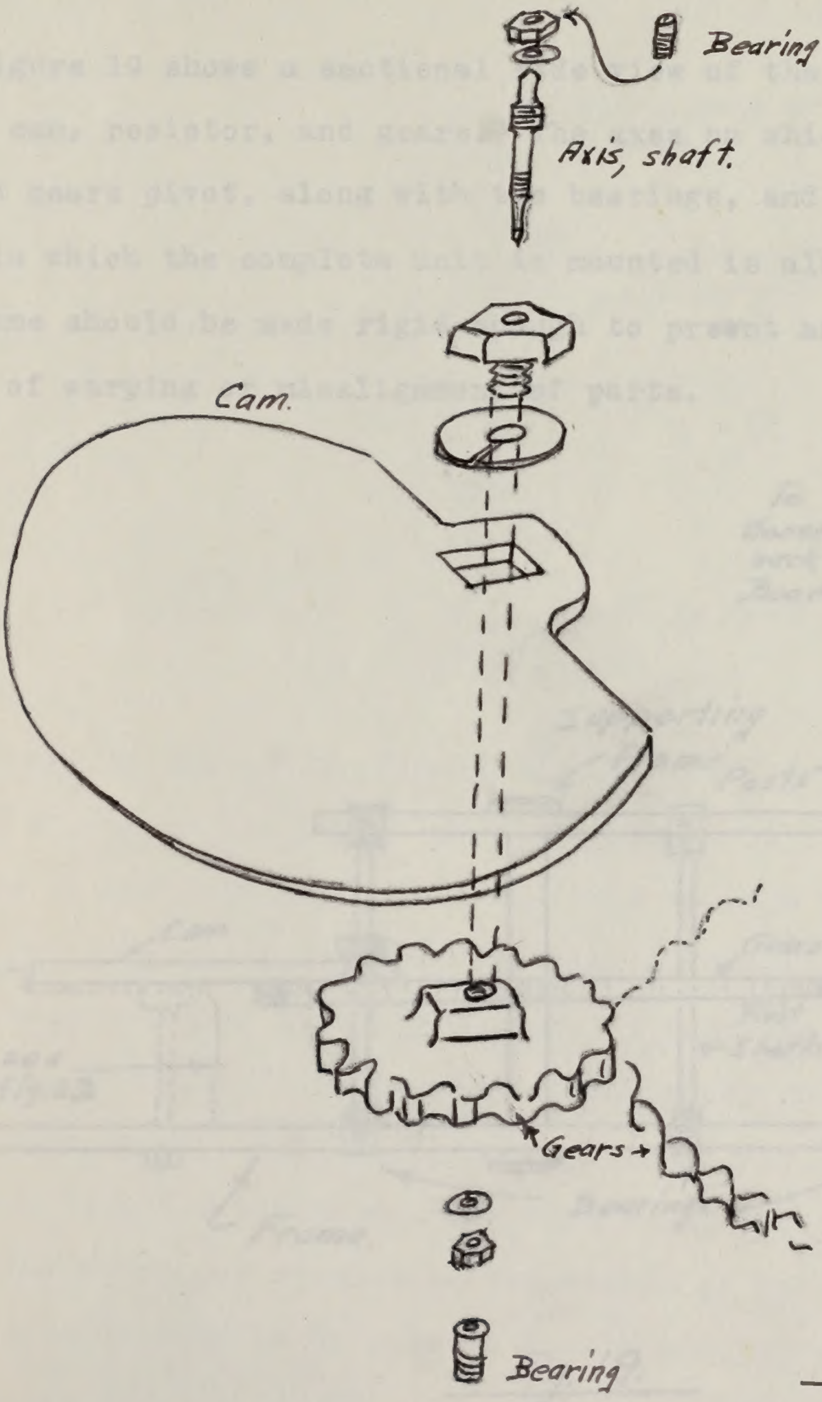


Fig. 18.

6. Assembly of Cam, Resistor, and Contact Slider at Boom.

Figure 19 shows a sectional side view of the assembly of the cam, resistor, and gears. The axes on which the cam and gears pivot, along with the bearings, and the frame in which the complete unit is mounted is also shown. The frame should be made rigid enough to prevent any possible danger of warping or misalignment of parts.

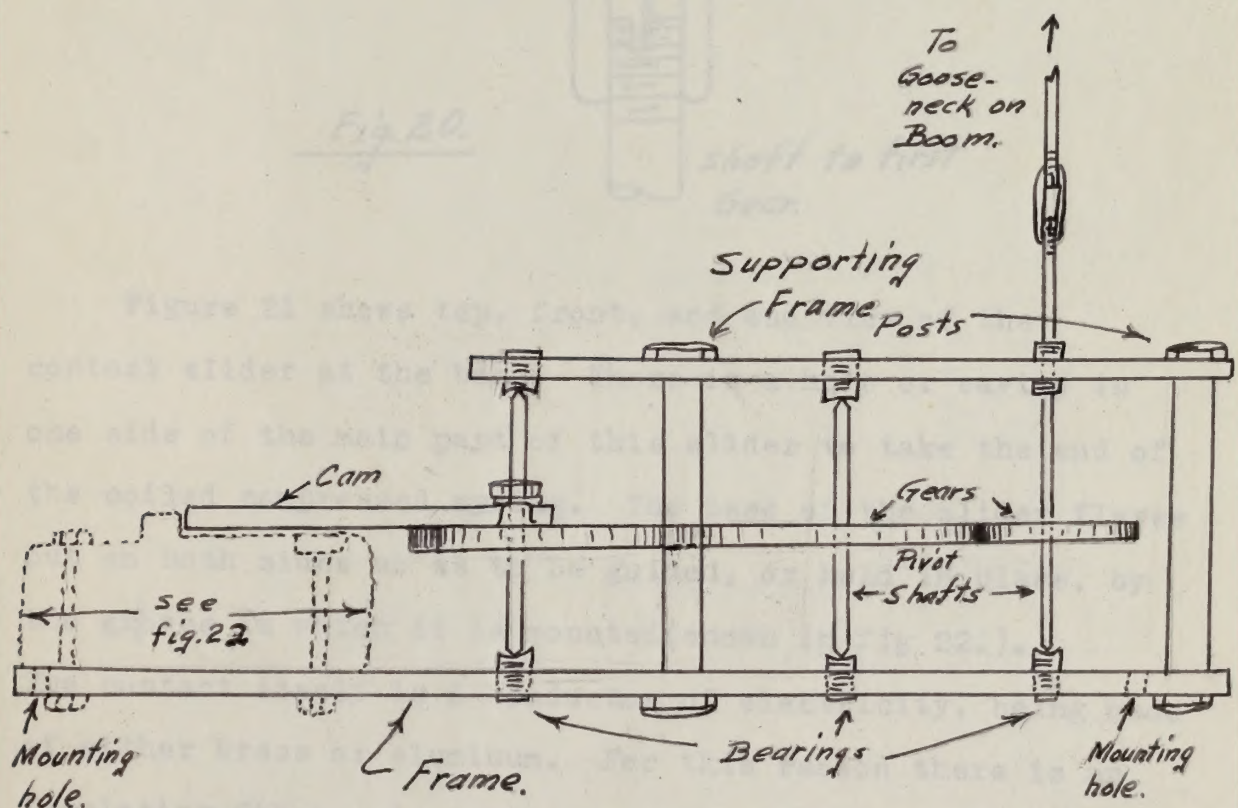


Fig. 19.

Figure 20 shows a larger detail of the collar and connection between the gooseneck on which the boom is mounted and the shaft to the first cam. This coupling link is adjustable to facilitate assembling.

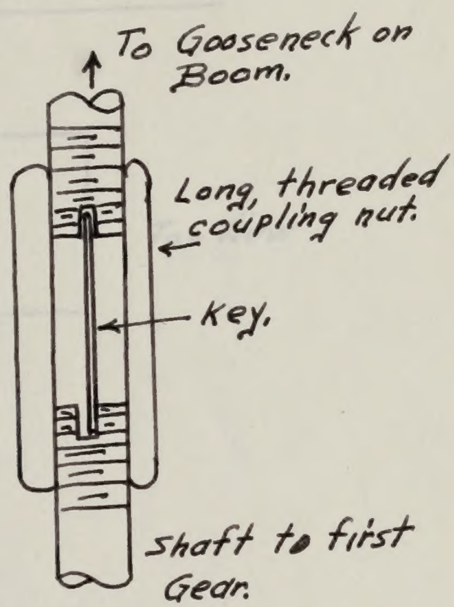


Fig. 20.

Figure 21 shows top, front, and end view of the contact slider at the boom. There is a hole or cavity in one side of the main part of this slider to take the end of the coiled compressed spring. The base of the slider flares out on both sides so as to be guided, or held in place, by the groves in which it is mounted(shown in fig 22.). The contact itself is a conductor of electricity, being made of either brass or aluminum. For this reason there is an insulating fibre pad mounted on the bottom of the slider. The purpose of this is to provide insulation between the body of the contact slider and the resistor R_b. A spring contactor under the slider makes the contact with R_b.

Contact Slider.

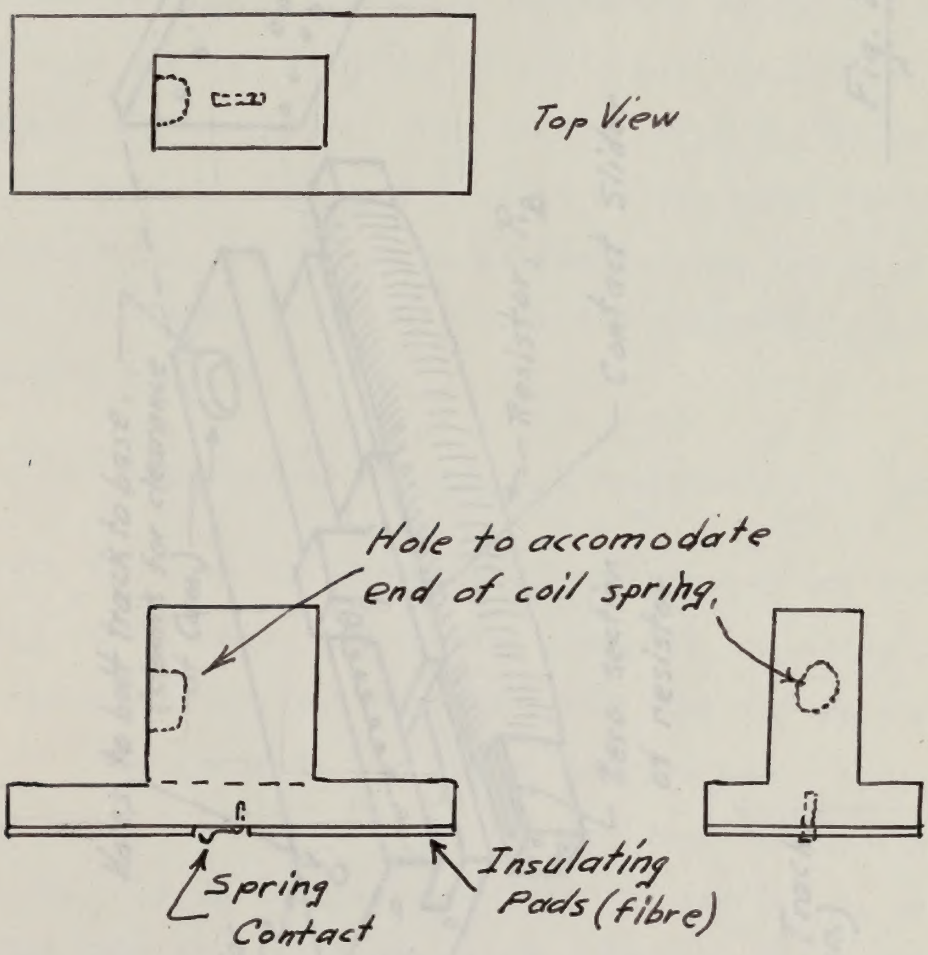
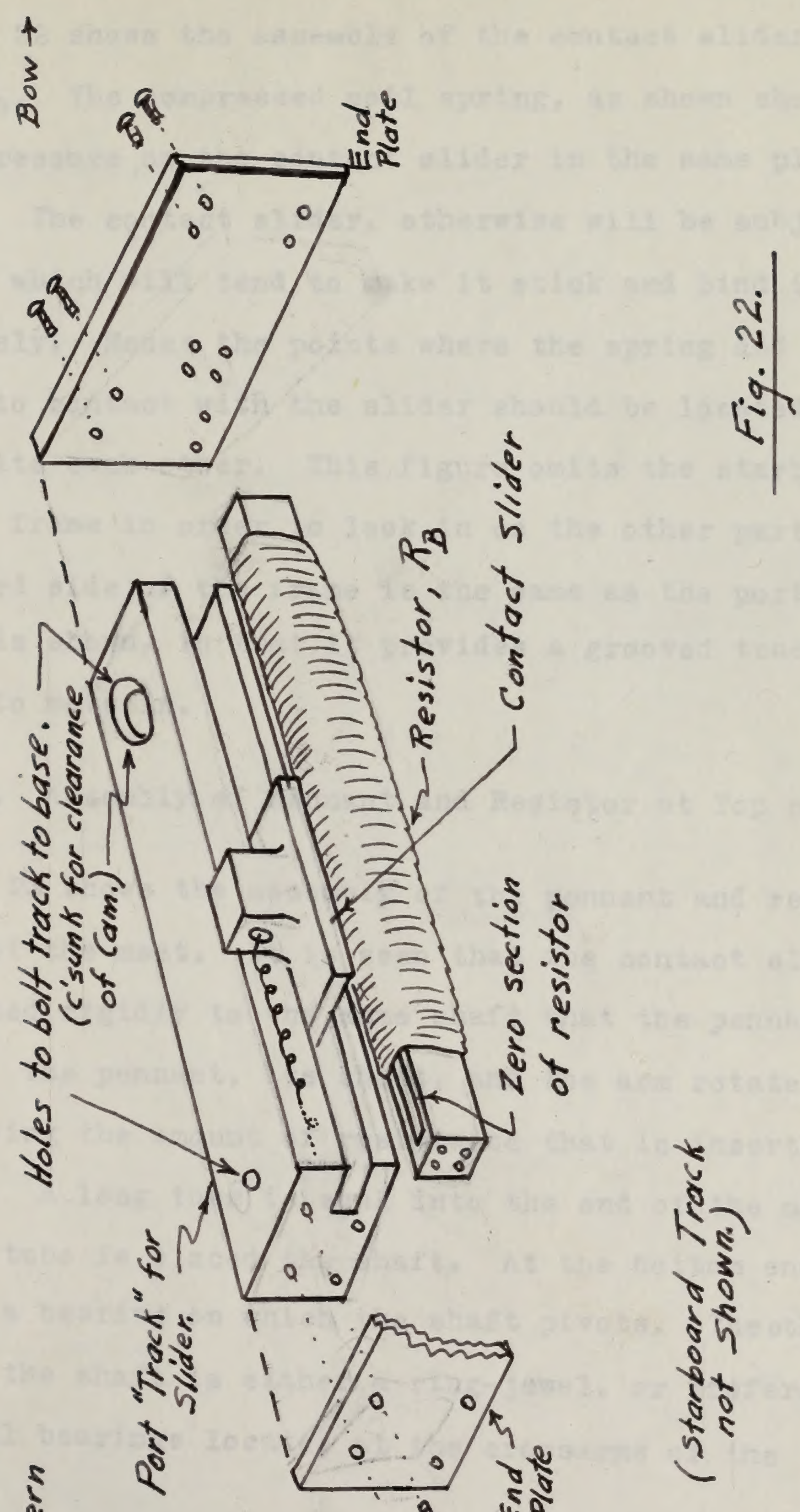


Fig. 21.



← Stern
Bow →
End Plate
Holes to bolt track to base.
(c'sunk for clearance of Cam.)
Resistor, R_B
Contact Slider
Zero section of resistor
Port "Track" for Slider.
End Plate
(Starboard Track not Shown.)

Fig. 22.

Figure 22 shows the assembly of the contact slider, and resistor, R_b. The compressed coil spring, as shown should exert its pressure on the contact slider in the same plane as the cam. The contact slider, otherwise will be subjected to a torque which will tend to make it stick and bind instead of move freely. Hence the points where the spring and the cam come into contact with the slider should be located right opposite each other. This figure omits the starboard side of the frame in order to look in on the other parts. The starboard side of the frame is the same as the port side which is shown, in that it provides a grooved track for the slider to move in.

7. Assembly of Pennant and Resistor at Top of Mast

Figure 23 shows the assembly of the pennant and resistor at the top of the mast. It is seen that the contact slider arm is mounted rigidly to the same shaft that the pennant is mounted on. The pennant, its shaft, and the arm rotate together, varying the amount of resistance that is inserted in the circuit. A long tube is sunk into the end of the mast, and in this tube is placed the shaft. At the bottom end of the tube is a bearing on which the shaft pivots. The other support for the shaft is either a ring-jewel, or preferably a set of ball bearings located at the crossarms of the resistor.

Fig. 23.

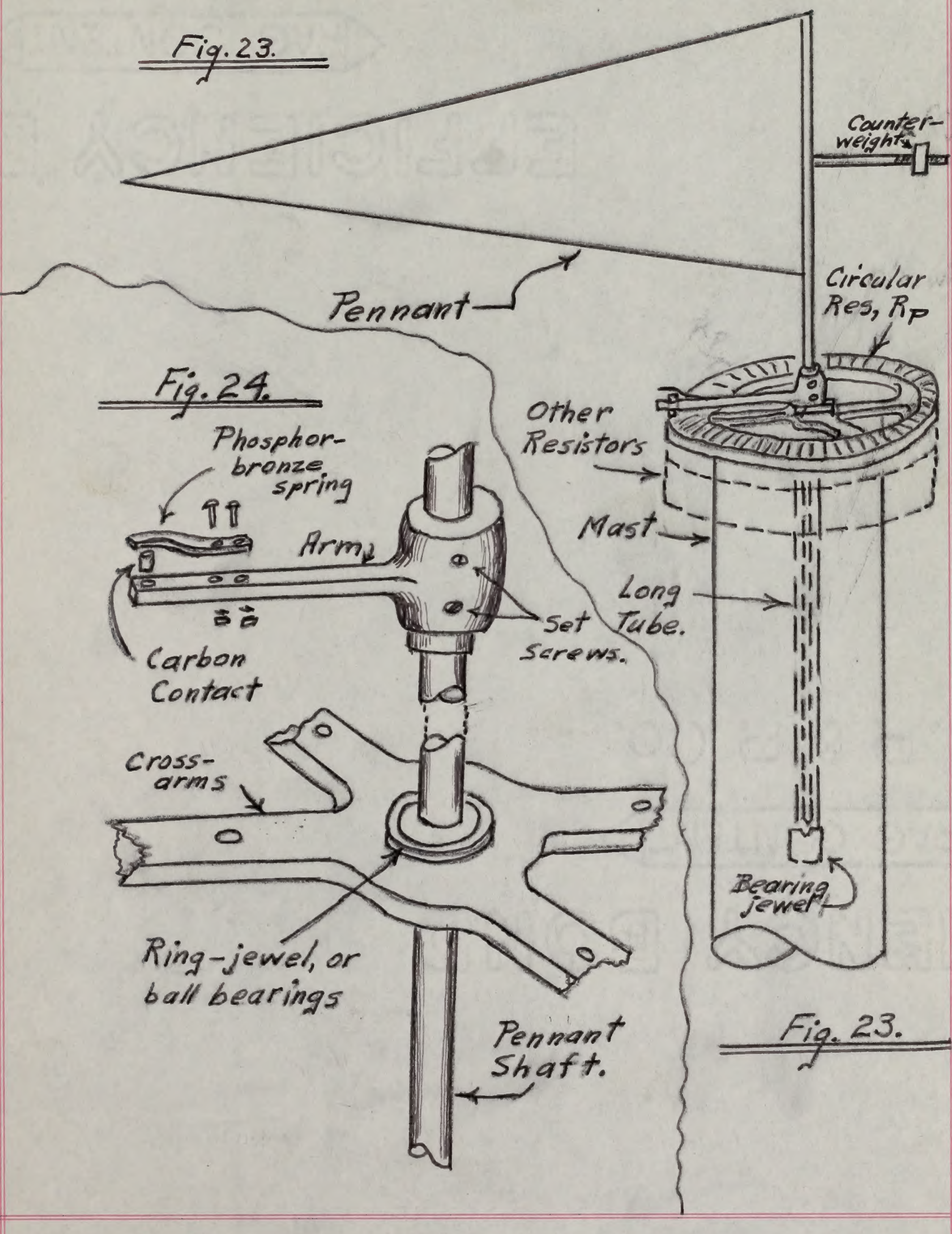


Fig. 24.

Fig. 23.

Figure 24 shows the details of the cross arm and contact slider arm assembly.

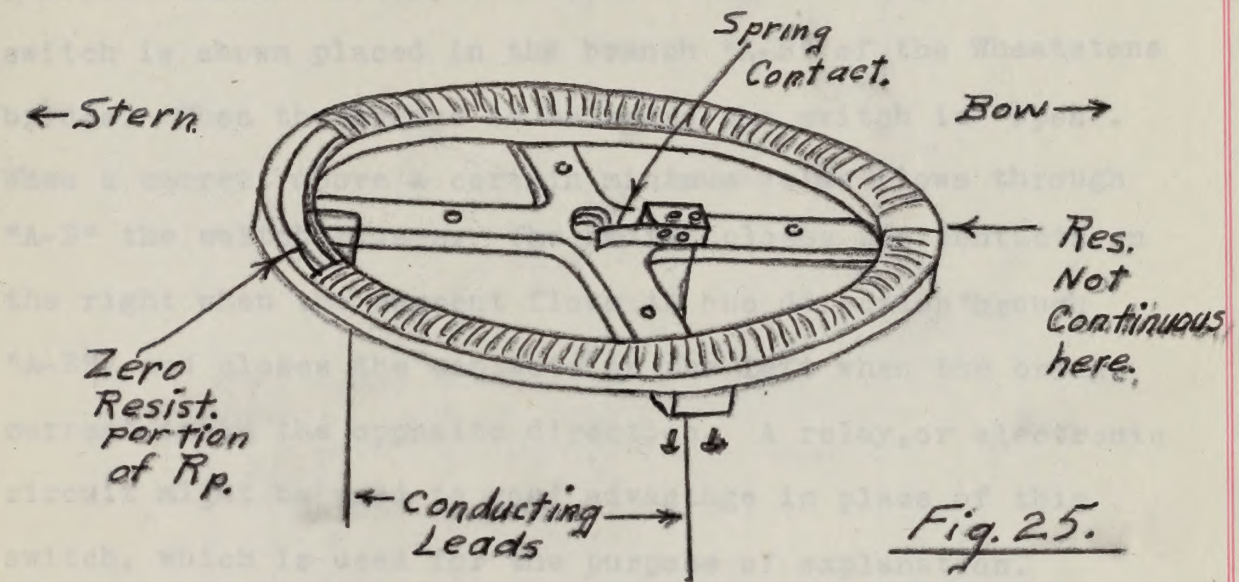


Fig. 25.

Figure 25 shows the details of the resistor ring at the top of the mast. The location of the leads making connection with this resistor are shown, as well as a spring contactor to make electrical contact with the hub of the contact slider arm.

It will be noticed in fig.24 that the hub of the contact slider arm is provided with a cylindrical section at its lower extremity against which this spring contact slides when the arm rotates.

There are additional resistor coils which will eventually be mounted at the top of the mast, and which will be referred to later. These are merely shown dotted in figure 23.

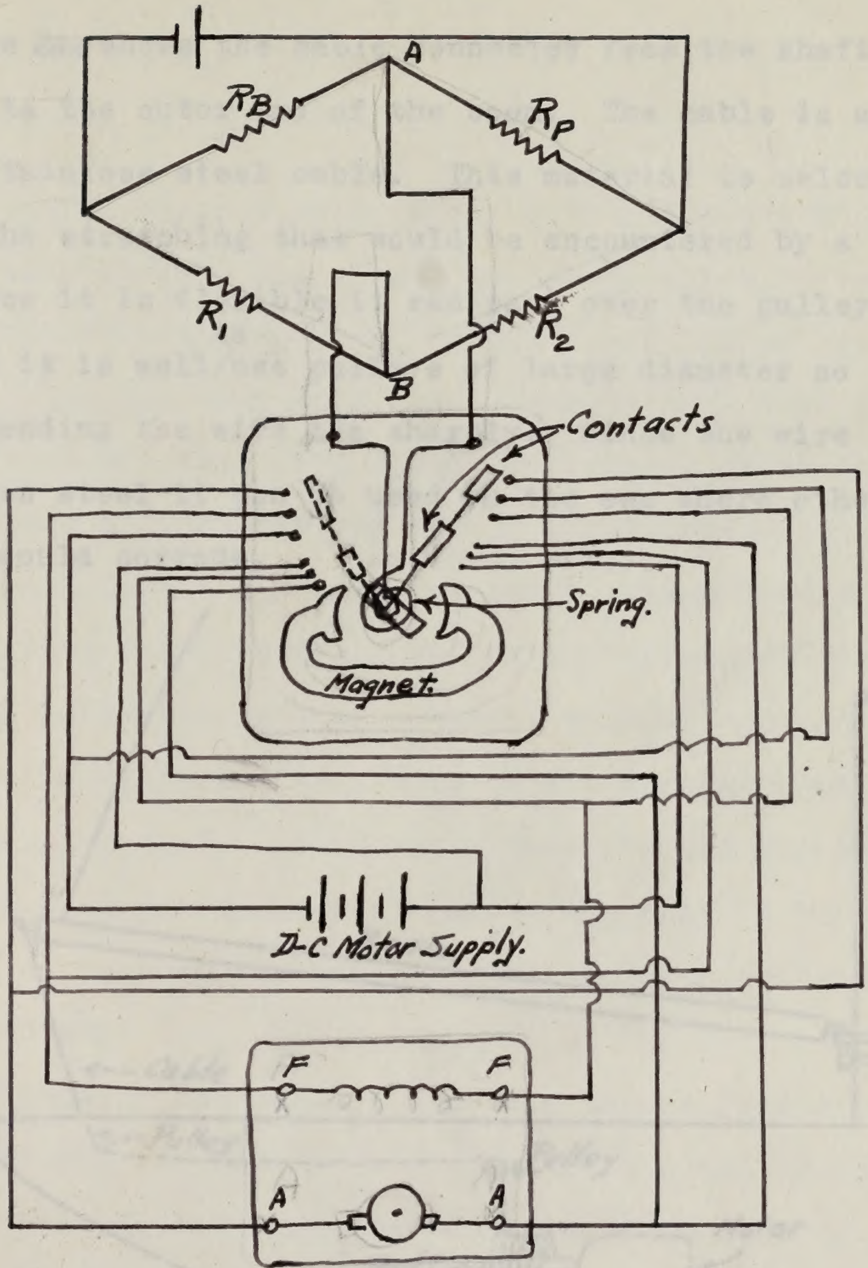
8. Motor Control of Sails.

Figure 26 is a schematic diagram of wiring for a switch, a direct current motor, and the Wheatstone bridge. A switch is shown placed in the branch "A-B" of the Wheatstone bridge. When the bridge is balanced the switch is "open". When a current above a certain minimum value flows through "A-B" the switch closes. The switch closes the contacts on the right when the current flows in one direction through "A-B", and closes the contacts on the left when the bridge current is in the opposite direction. A relay, or electronic circuit might be used to good advantage in place of this switch, which is used for the purpose of explanation.

Tracing the wiring from the switch to the motor will show that the direction of rotation of the motor will reverse when the contacts are shifted from one side to the other in the switch. The switch shown works the same principle as a direct current, moving coil, permanent magnet, D'Arsonval instrument, with zero center.

The neutral position of the switch is open. Thus when balanced conditions exist in the bridge the motor is idle. Thus when the wind is striking the sails at the correct angle, the bridge is balanced, and there is no operation of the motor.

On the other hand if the wind is inclined to the sail at an incorrect angle, the bridge is unbalanced, the motor operates, pulling the sail in or letting it out. A cable is connected from the motor shaft to the outer end of the boom for this.



F-F, connections to field.

A-A, connections to armature.

Fig. 26.

Figure 26-a shows the cable connected from the shaft of the motor to the outer end of the boom. The cable is a flexible stainless steel cable. This material is selected to avoid the stretching that would be encountered by a rope. Since it is flexible it can pass over the pulleys shown, but it is well to use pulleys of large diameter so as to avoid bending the wire too sharply. Since the wire is of stainless steel it can be used on the sea where other materials would corrode,

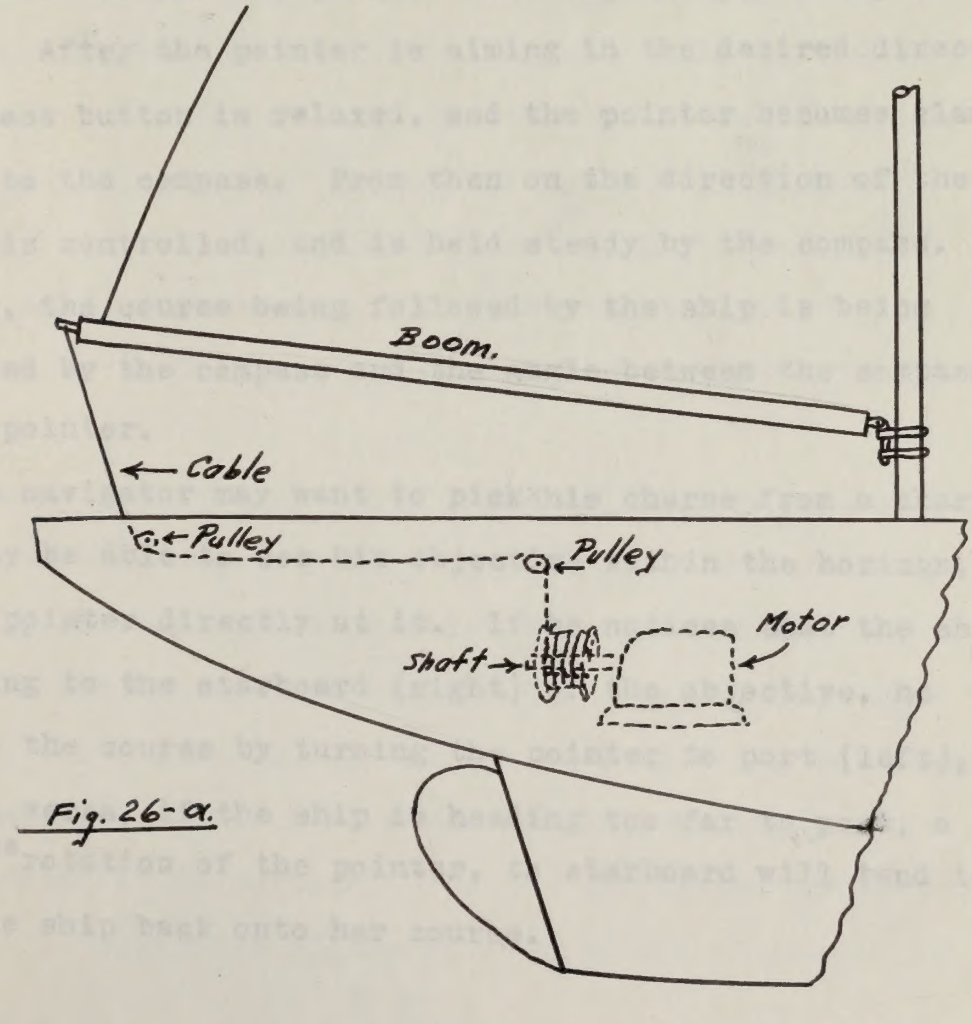


Fig. 26-a.

III. Selecting and Holding Course - When Not Tacking.

A. Compass and Pointer.

In order to steer a ship fitted with automatic control the operator need only aim a small pointer, which is located on board ship near the compass, in the direction he wished to travel, and the ship will steer herself onto this course. The pointer is provided with a release button. When the operator wants to turn the pointer he first presses the release button which allows the pointer to swing independently of the compass. After the pointer is aiming in the desired direction the release button is relaxed, and the pointer becomes clamped rigidly to the compass. From then on the direction of the pointer is controlled, and is held steady by the compass. Actually, the course being followed by the ship is being controlled by the compass and the angle between the compass and the pointer.

The navigator may want to pick his course from a chart, or he may be able to see his objective within the horizon, and aim the pointer directly at it. If he notices that the ship is heading to the starboard (right) of the objective, he corrects the course by turning the pointer to port (left), and vice versa, if the ship is heading too far to port, a clockwise rotation of the pointer, to starboard will tend to bring the ship back onto her course.

It should be mentioned that the operator may have errors due to currents and sideslip to correct for in his navigating. The actual steering of the ship, by merely aiming a pointer is as simple, if not simpler than steering an automobile.

If the objective happens to lie dead to windward, or within an angle of 45 degrees (for example) either side of the dead ahead position, the ship must tack in order to arrive at her destination. As long as the angle between the pennant and the hull is less than 45 degrees, the ship must tack. The angle between the wind and the hull is maintained constant when tacking as will be seen later. As the ship sails along the operator keeps aiming the pointer at the objective, and when the objective comes aft to the point where it is 90 degrees away from the direction of the hull the automatic control makes the ship "come about" onto the other tack.

At any instant on a tack, the operator may decide that he wants to take over manually to tack or to swing the ship so as to avoid some obstacle which might be in the way. Switches could be supplied which would entirely disengage the automatic control and allow the operator to take over manually.

However, reflecting for a moment, we recall that the ship's direction is controlled by the operator's merely changing the direction of the pointer at the compass. So

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However, reflecting for a moment, we recall that the ship's direction is controlled by the operator's merely changing the direction of the pointer at the compass. So

the operator would do better, in general, to leave the ship on automatic control and make the sudden changes in course by moving the pointer. In this way, not only is the ship steered by rudder, but at the same time the sails are trimmed to give the maximum efficiency while the ship is turning.

If the ship were to be taken off of automatic control, and put on manual, one person would have to tend the tiller, and the same person or someone else would have to jump to take care of changing the sails if necessary. Often, due to laziness on the part of the crew, the sails are not trimmed or slackened under just these circumstances of sudden changes to avoid objects. If the sails were adjusted, the vessel would handle more gingerly, and increase the safety under these situations.

This response of the ship is felt more pronounced when on a reach, pointing, or running, when it is desired to fall off to avoid an obstacle, in general, than when pointing up to avoid an obstacle, especially in dusty going.

Therefore the automatic control appears to be safer, and easier , and more efficient, although possible not as split-hair fast as a well-trained crew, for sudden unexpected requirements in the changing of course.

Automatic compass control of the ship would come in handy when sailing in weather of practically zero visibility, or at night, or in the daytime when long hours on end make

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Automatic compass control of the ship would come in handy when sailing in weather of practically zero visibility, or at night, or in the daytime when long hours on end make

steering a ship, and watching the sails a tedious job.

Under these conditions let all hands (with the possible exception of a look-out) go about other duties, and throw the ship on automatic control, lightening the burden of the crew.

Now an ordinary yachting compass of length up to about six or eight inches may not hold steady enough in a rough chop to provide the required control. As the ship rolls and pitches the compass will change its indications somewhat, oscillating back and forth. This is good enough for a pilot to find his course by, since he can take the average about which the compass is swinging. But the automatic control would be apt to have the motors controlling sail and rudder starting and stopping unnecessarily for such oscillations. Under these conditions it might be well to use a gyro-compass to obtain a steadier indication, and eliminate these oscillations.

B. Pointer and Shade.

Figure 27 shows the external appearance of the compass, pointer, gunsights mounted on the pointer, and a box containing the associated equipment. This box may be located out in the cockpit when sailing under pleasant weather, or may be arranged to be moved down into the cabin when the weather is foul, thereby making sailing conditions easier. The box is to be light tight since two phototubes are located inside.

Fig. 27.

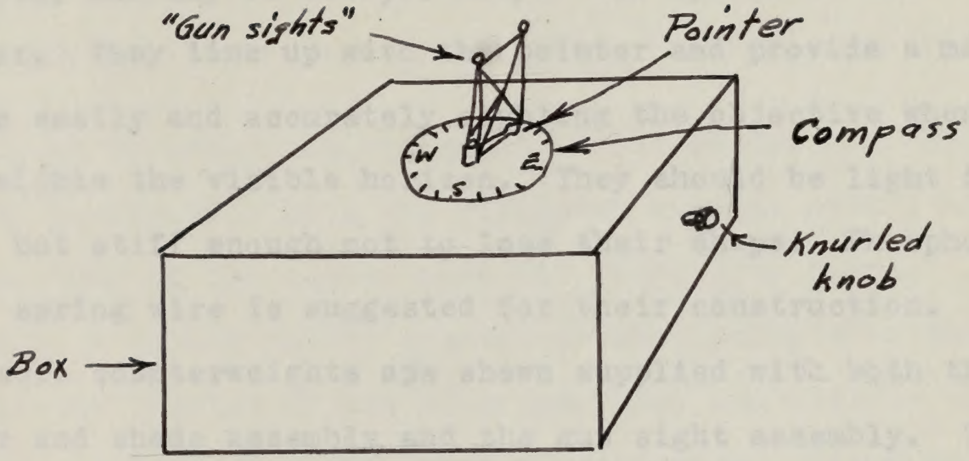


Figure 28 shows the details of the assembly of the pointer and "shade", with "gun sights"attached. The shade is rigidly coupled to the shaft on which the pointer is mounted. Therefore any change in the direction of the pointer is accompanied by the same change in the direction of the shade. Now, it was seen that the pointer is rigidly coupled to the compass whenever the operator is not actually setting the pointer. Therefore the direction of the shade is controlled by the compass. The materials used in the construction of the pointer, its shaft, and the shade should be of light weight material such as aluminum, or duraluminum, so as reduce their drag on the compass.

However they must be rugged enough to eliminate any possibility of loosing proper alignment.

The gun sights are also shown in figure 28. These are removable, and may be used, or not, at the option of the operator. They line up with the pointer and provide a means of more easily and accurately sighting the objective when it is within the visible horizon. They should be light in weight but stiff enough not to lose their shape. Phosphor-bronze spring wire is suggested for their construction. Adjustable counterweights are shown supplied with both the pointer and shade assembly, and the gun sight assembly. Thus no unbalanced weights will be imposed upon the compass.

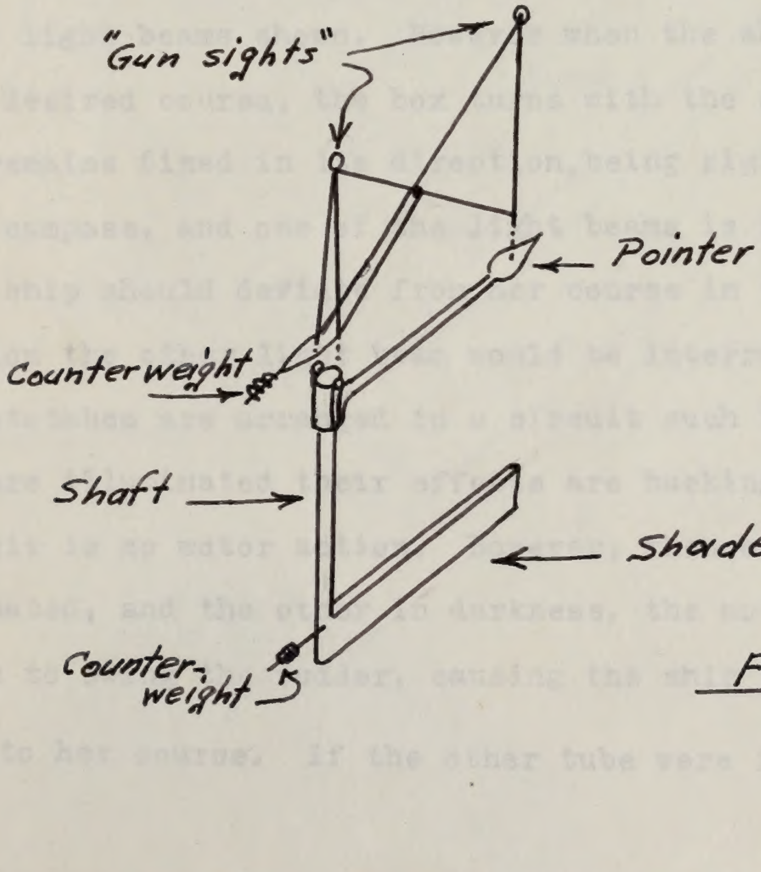


Fig. 28.

The main supports for the gun sights consists of two small tubes attached along side of the pointer shaft. These tubes are reamed out to obtain a friction fit for mounting the gun sights.

C. Operation of Pointer and Shade for Motor Control.

Figure 29 shows the equipment inside of the box which is shown in fig.27. Only the equipment used to obtain automatic control of the rudder when not tacking is shown. Equipment to obtain rudder control automatically when tacking will also be located within this same box, and will be shown later when discussed. The shade is so located that when the ship is sailing correctly, it does not interrupt either of the two light beams shown. However when the ship falls off of the desired course, the box turns with the ship, the shade remains fixed in its direction,being rigidly attached to the compass, and one of the light beams is interrupted. If the ship should deviate from her course in the other direction the other light beam would be interrupted. The two phototubes are arranged in a circuit such that when both tubes are illuminated their effects are bucking each other, and their is no motor action. However, when one tube is illuminated, and the other in darkness, the motor action is such as to swing the rudder, causing the ship to be steered back onto her course. If the other tube were in darkness,

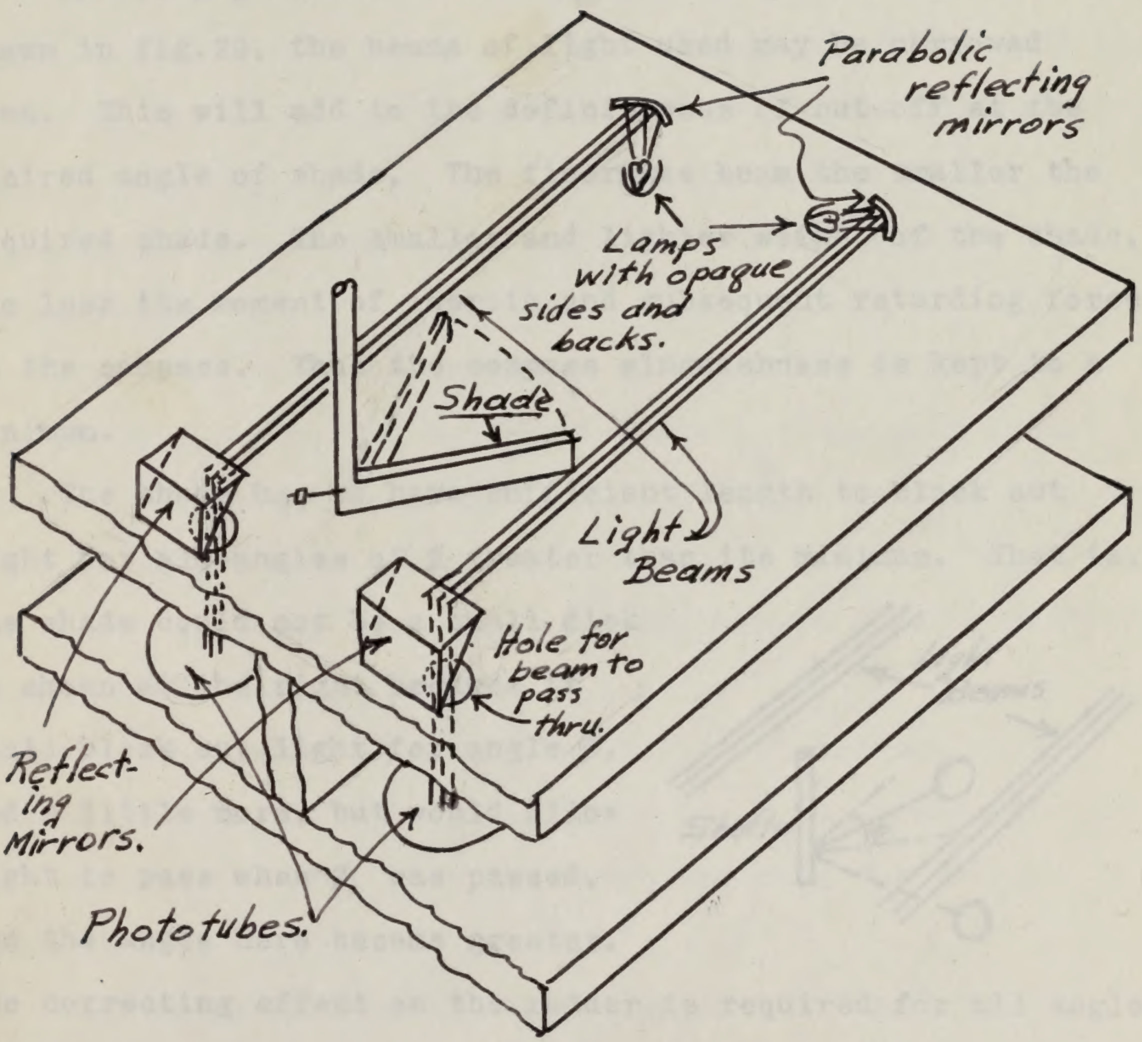
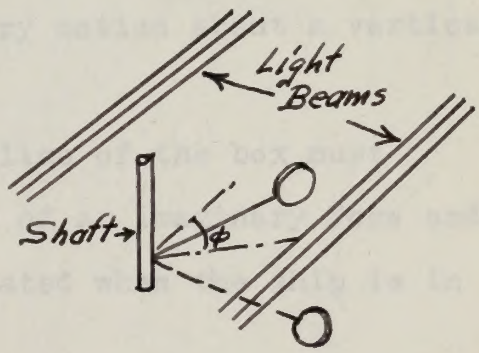

Parabolic
reflecting
mirrors
Lamps
with opaque
sides and
backs.
Shade
Light
Beams
Hole for
beam to
pass
thru.
Reflect-
ing
Mirrors.
Phototubes.

Fig. 29

due to the shade's swinging the other way, and conditions are reversed; the motor action is also reversed, the rudder is swung in the opposite direction to again restore the ship to her course.

By using paraboloid reflecting mirrors at the lamps shown in fig.29, the beams of light used may be narrowed down. This will add to the definiteness of cut-off at the desired angle of shade. The finer the beam the smaller the required shade. The smaller and lighter weight of the shade, the less its moment of inertia and subsequent retarding force on the compass. Thus the compass sluggishness is kept to a minimum.

The shade has to have sufficient length to block out light for all angles of Ø greater than its minimum. That is, the shade could not be a small disk as shown at the right because it would block out light for angle Ø, and a little more, but would allow light to pass when Ø was passed, and the angle here became greater.



The correcting effect on the rudder is required for all angles from Ø up.

The shade, and interior of the box, and the other objects within the box in so far as possible should be painted with dark, non-reflecting surfaces, to minimize stray light.

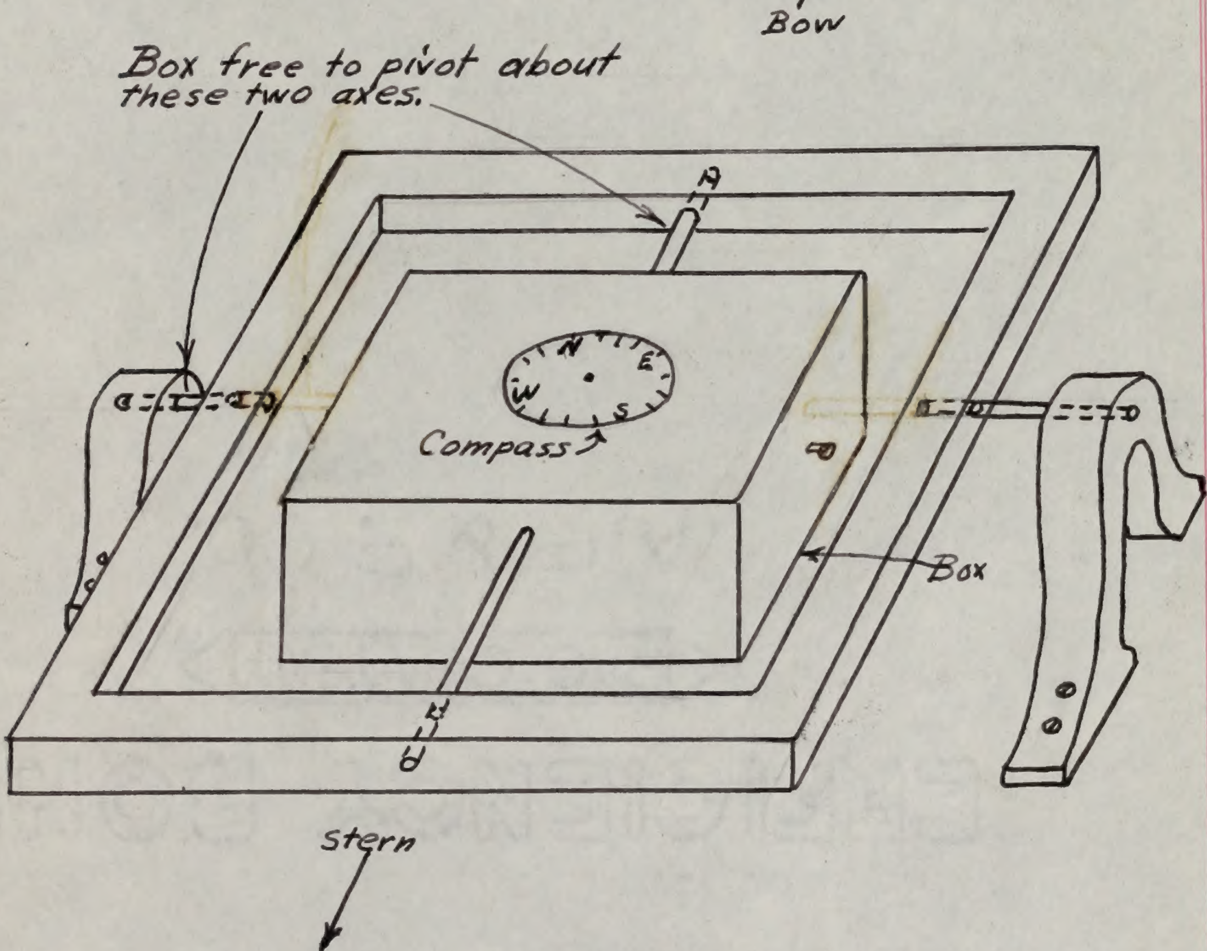
The plane of the compass must always remain horizontal. The pointer is always in the plane of the compass. The shaft to which the pointer is attached is perpendicular to the pointer, and the shade attached to the pointer shaft is parallel to the pointer. The relationships between the light beams and the shade must be independent of the roll and pitch of the ship, therefore this entire box containing compass, phototubes, lamps, etc., shown in figures 27 and 29, must always remain in a horizontal plane, the same as the compass itself.

This may be accomplished by mounting the entire box in gimbals similar to the manner in which a compass is often mounted. This is shown in fig.30. However, it should be noted that while the entire box is to remain in a horizontal plane, it is not to swing freely in a rotary motion about a vertical axis, as the compass does.

Rather the fore and aft centerline of the box must remain always in the vertical plane of an imaginary fore and aft axis of the ship (this axis located when the ship is in calm water),

Now let us consider the operation of the "shade". This remaining horizontal of the box, permits the pointer to remain pointing at the destination (or more accurately speaking pointing in the desired direction of the ship's motion) and to be independent of any roll and pitch of the ship.

Note: The compass box pivots about only 2 axes, and remains parallel to direction ship is heading.



(Compass itself is free to pivot about three mutually perpendicular axes.)

Fig. 30.

Weights low in box keep it horizontal.

Once the pointer is set, and clamped in a fixed position with respect to the compass, the compass keeps the pointer aiming in the right direction. Then, if the ship sails along its correct course, there will be no requirement for rudder action. But as soon as the ship veers from her course by more than a desired angle (equal to Ø as previously mentioned) rudder action causes the ship to turn back onto her course.

When the ship again is on her course the rudder action ceases. Note in connection with this rudder action that the force on the rudder is greatly decreased by properly "balancing" the ship. This refers to balancing the center of effort of the sails against the center of lateral resistance of the hull and keel or centerboard. Therefore the ship should be as finely balanced as possible. Unbalance in this respect places an extra and unnecessary burden on the motor controlling the rudder. The rudder must continually be exerting a force in one direction or the other in order to keep a ship on her course when the ship is not properly balanced. This is known as having a "Weather helm" or a "Lee helm". Incidentally, a weather helm or a lee helm causes a drag on the rudder, and slows the vessel down. So if it is eliminated by proper balancing, the efficiency and speed of the ship will increase, as well as decrease the burden on the motor controlling the rudder.

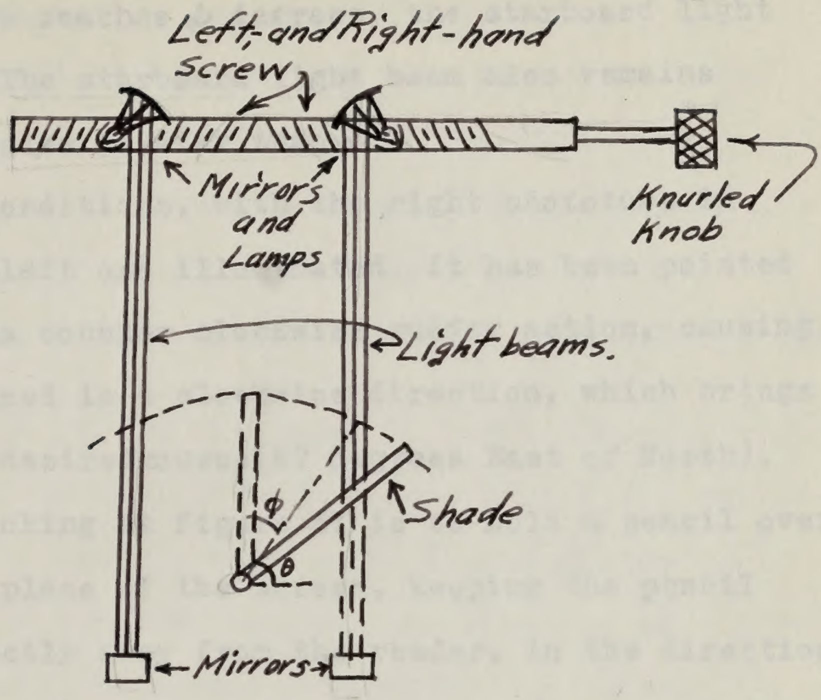


Fig. 31.

Figure 31 shows the action of the shade in interrupting the light beams. The shade is constructed parallel to the pointer. The pointer is set manually onto a course and then clamped to the compass. For an example, assume the desired course lies 67 degrees East, or clockwise, of North. Then, when the ship is sailing 67 degrees East of North the shade is parallel to the fore and aft centerline of the hull. Both phototubes are illuminated, and no rudder action is present. Now let's assume that the ship starts to deviate from her course, say in a counter-clockwise direction. The "shade" still remains aiming 67 degrees East of North. On fig.31 it is seen that angle θ decreases as the ship turns counter-clockwise. When the angle by which the ship is

off her true course reaches ϕ degrees, the starboard light beam is cut off. The starboard light beam also remains cut off for all angles greater than ϕ .

Under these conditions, with the right phototube in darkness, and the left one illuminated, it has been pointed out that there is a counter clockwise rudder action, causing the ship to be turned in a clockwise direction, which brings her back onto the desired course(67 degrees East of North).

One way of looking at figure 31 is to hold a pencil over the figure in the place of the screen, keeping the pencil aiming always directly away from the reader, in the direction the ship should travel. Now rotate the page in a counter-clockwise direction, just as the ship would turn in the previous illustration. This is to illustrate how the shade, with its direction fixed in relation to the compass, will cut off the right hand light beam when the ship deviates from her course in a counter-clockwise direction. Thus a correcting rudder action is automatically called into play.

Similar relationships hold true when the ship err's from her true course in the opposite (clockwise) direction.
In this case:

1) The shade blocks out the port (left) light beam.

2) The left phototube is in darkness, while the right one is illuminated.

3) This causes a clockwise rudder action, tending to turn

the ship counter-clockwise, back onto her course.

4) When the ship's direction has been corrected, and she is again on her course, the shade is parallel with the fore-and-aft centerline of the hull, both phototubes are illuminated, and there is zero rudder action.

D. Adjustment of Closeness with which Ship Holds Course.

Angle Ø, in fig. 31, is the angle or error through which the ship is allowed to turn through before corrective rudder action is used. The smaller this angle Ø, the closer the ship will be held to her true course, and also the more often the rudder action will be used. Conversely, the larger the angle Ø, the more the ship will be allowed to deviate from her course, andthe less often the rudder action will be called into play.

The requirements for tollerance on the angleØ vary. For example, after racing eight or ten miles, the two leading ships sometimes are separated by only a few feet (or less), when crossing the finish line. Although this is often caused by one yacht "blanketing" the other, it is not at all uncommon for two yachts which have gone off onto different tacks to come together, after sailing apart for several miles, so close that one must yield right of way to the other, in order to avoid a collision.

Under such circumstances the angle Ø must be kept to

an absolute minimum, say in the order of one or two degrees, or less if possible.

An extreme case of the oppoite requirements, where the angle ϕ would be allowed to be quite large, say in the order of ten degrees, would be when cruising in "dusty weather", with heavy winds, and a rough sea. The ship may be beating along, and as she slowly rises on one wave, and then rushes down the other side as it passes, her direction of sailing will, in general, be changed. But the average direction will be toward the objective even though the ship heads in the desired direction only a small fraction of the time. Under these conditions it is wasted effort to try maintain a small angle ϕ. The ship need not be held to her course as closely as when racing, for example.

The angle ϕ may be quite readily adjusted by mounting the two lamps with their corresponding reflectors on a track, and varying the distance between the light beams. This may be accomplished by moving the two lamps with their reflectors in, closer together, or out further apart. These two lamps and reflectors could be mounted as shown in fig.31.

Their positions along the track is controlled by a screw having a left-hand and a right-hand thread, The left-hand thread controls the position of one of the lamps and its reflector, while the right-hand thread controls the position of

the other lamp and its reflector. Rotating the screw in one direction brings the two units closer together, reducing angle ϕ, while rotating the thread in the other direction moves the lamps and reflectors farther apart, increasing the angle ϕ.

The individual ship can be adjusted for a desirable all-round working angle ϕ and left there. Or the operator may adjust ϕ by turning a knurled knob on the side of the "compass box", which is connected to the end of the adjusting screw. Shown in figs.27 and 31. The adjustment would best be made by trying out the individual ship under various weather conditions and sailing requirements.

It should be noted the the setting of the angle ϕ does not necessarily mean that the ship will hold to within ϕ degrees of her true course. Rather, when the ship deviates from her true course by an angle equal to or greater than ϕ, the mechanism for correcting her direction comes into play. Shortly after this, depending on the ship, and the conditions prevailing, the ship will be brought back to within ϕ degrees or less of her true course.

Hence a means is provided for adjusting the closeness with which the ship will try to cling to her true course.

IV. Automatic Selecting and Holding Course- When Tacking.

A. Tacking Zone.

The discussion thus far has been confined to the case

when the ship has been able to head in the direction of the pointer, and proceed toward her destination without tacking.

However, if the destination lies directly to windward, or within a certain zone to windward, the ship must tack in order to arrive there.

The problems of the ship's knowing when conditions are such that it must tack back and forth, and also how the ship executes the actual maneuver of "coming about" will now be discussed.

The angle between the pennant and the pointer, that is, the angle between the apparent wind direction and the direction of the objective from the ship, will be taken as the angle between a vector aiming in the direction from which the wind is coming (this is the direction for which a wind is named; for example, a northwest wind blows from the northwest, not to the northwest), and a vector aiming in the direction in which the pointer is aiming.

The angle OSW in figure 32 is the angle at the ship

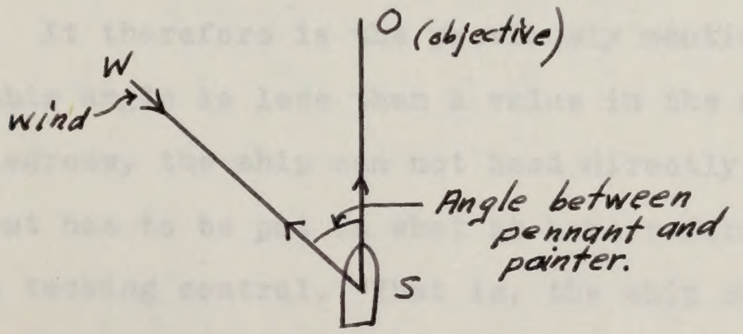


Fig. 32.

between the wind and the direction of the objective from the ship. When this is less than a value in the neighborhood of 45 degrees, the ship must tack in order to reach the objective. The angle OSW will vary from one ship to another, since some ships will "point higher", that is, sail closer into the wind than others. This variation is noticed even between individual ships in a one design class of racing yachts, where each individual yacht is built to the same specifications as all the others in her class. It is also noticed on any one ship when different suits of sails are used. A ship will point higher when carrying a flat suit of sails than when carrying a suit having considerable depth of curvature.

B. Critical Changeover Angle Between Tacking and Non-Tacking Control.

1. Determination of Critical Changeover Angle.

By the critical changeover angle is meant that angle which constitutes the dividing line between tacking and non-tacking control. The angle is that formed between pennant and pointer. It therefore is the previously mentioned angle OSW. When this angle is less than a value in the neighborhood of 45 degrees, the ship can not head directly for its objective, but has to be put on what is here referred to as automatic tacking control. That is, the ship can not maintain headway if it tries to operate as it would when

under automatic non- tacking control, and head straight for the objective.

Figure 33 shows how this critical angle is measured, the equipment for adjusting it, and the switch that throws the control back and forth between automatic tacking and

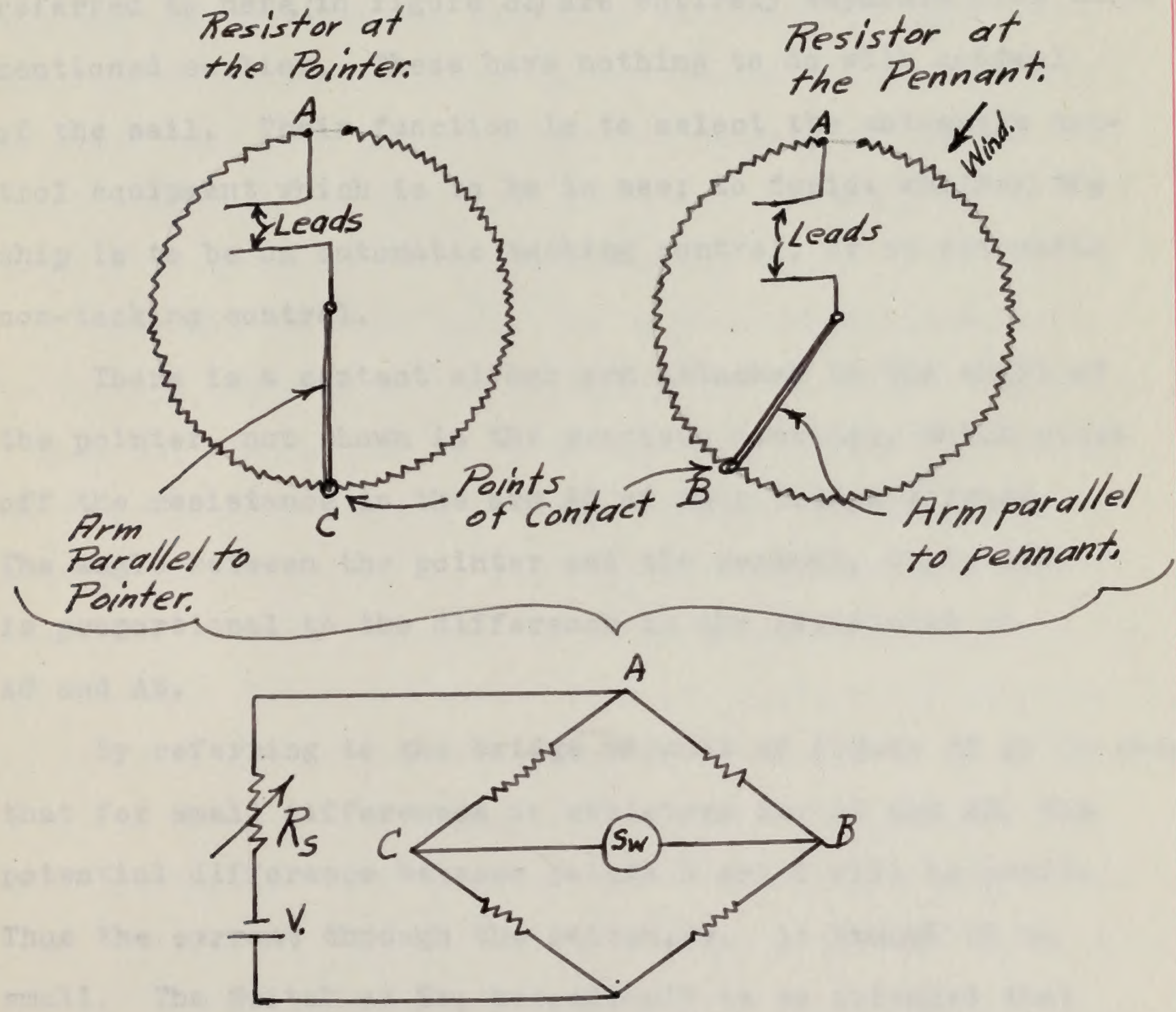


Fig. 33.

automatic non-tacking control. At the pennant the resistance in this bridge circuit is AB. At the pointer the resistance in this bridge circuit is AC. Note here that this bridge circuit is not the one mentioned earlier.

These resistors, the bridge circuit, and the switch referred to here, (in figure 33) are entirely separate from those mentioned earlier. These have nothing to do with control of the sail. Their function is to select the automatic control equipment which is to be in use; to decide whether the ship is to be on automatic tacking control, or on automatic non-tacking control.

There is a contact slider arm attached to the shaft of the pointer, not shown in the previous drawings, which picks off the resistance in the arm AC of this bridge circuit. The angle between the pointer and the pennant, angle OSW, is proportional to the difference in the resistance at AC and AB.

By referring to the bridge circuit of figure 33 it is seen that for small differences in resistors for AC and AB, the potential difference between points B and C will be small. Thus the current through the switch, Sw, in branch CB is small. The Switch at Sw, accordingly is so arranged that when there is below a certain current passing through CB, the switch is not activated, or is "out". As the converse,

when the current through CB is above this certain value the switch is activated, or in its "in" position. When the switch is out, the ship is on automatic tacking control (recalling small current through CB as a result of small angle between pennant and pointer), while the ship is on automatic non-tacking control when the switch is activated or "in"(re-calling that switch is activated for large currents through CB which flow when the angle between pennant and pointer is large, which is the case when it is not necessary to be tacking in order to reach objective.).

Now, the critical angle can very easily be adjusted by varying the resistor at Rs, shown in the bridge circuit of figure 33. Increasing Rs means that the drops in the bridge will be less for a given battery voltage. Therefore, a greater difference in the resistances at AB and AC would be required to cause the same changeover current to flow through the switch. Likewise, a reduction in the value of the resistor Rs, will reduce the difference in resistors at AB and AC required for critical changeover current through the switch.

The higher into the wind the ship is capable of pointing, the smaller will be the angle between pennant and pointer at which she should be made to go about onto the other tack, and also the smaller the angle between pennant and pointer at which she should be set to go from tacking conditions to

when the current through CB is above this certain value the switch is activated, or in its "in" position. When the switch is out, the ship is on automatic tacking control (recalling small current through CB as a result of small angle between pennant and pointer), while the ship is on automatic non-tacking control when the switch is activated or "in" (recalling that switch in activated for large currents through CB which flow when the angle between pennant and pointer is large, which is the case when it is not necessary to be tacking in order to reach objective.)

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The higher into the wind the ship is capable of pointing, the smaller will be the angle between pennant and pointer at which she should be made to go about onto the other tack, and also the smaller the angle between pennant and pointer at which she should be set to go from tacking conditions to

non-tacking conditions, and vice versa.

This angle can be determined accurately only by experiment under actual sailing conditions. This is determined by first sailing the ship one one tack, close hauled, and pointing high, without "pinching"her, and thereby loosing speed. The direction of sailing is noted by the compass, and recorded. The ship is then put about onto the other tack, and the procedure repeated.

One half the difference in angle between the two compass readings is the minimum angle between direction of hull and direction of wind for which the wind will strike the sails at a great enough angle to drive the ship ahead at full speed. If the ship is pointed any closer into the wind than this her sails will start to luff and she will slow down.

This angle will vary from ship to ship. It will also be dependent on the shape of the sails used on any individual ship, thereby being different when a different set of sails is put onto a given ship.

2. Adjustment of Critical Changeover Angle.

This angle, once determined, can be adjusted for by either increasing or decreasing the resistor R_s of fig.33.

Now the two angles which will be referred to at this point are the following: 1) The angle between hull (or

the direction of sailing) and the pennant (or apparent wind direction) when the ship is pointing her highest. This is the angle the ship will set herself onto(method not yet described) when on automatic tacking. It is the angle shown in fig. 34, at the left. 2) the other angle is that between pennant and pointer. This is shown in fig. 34, at the center.

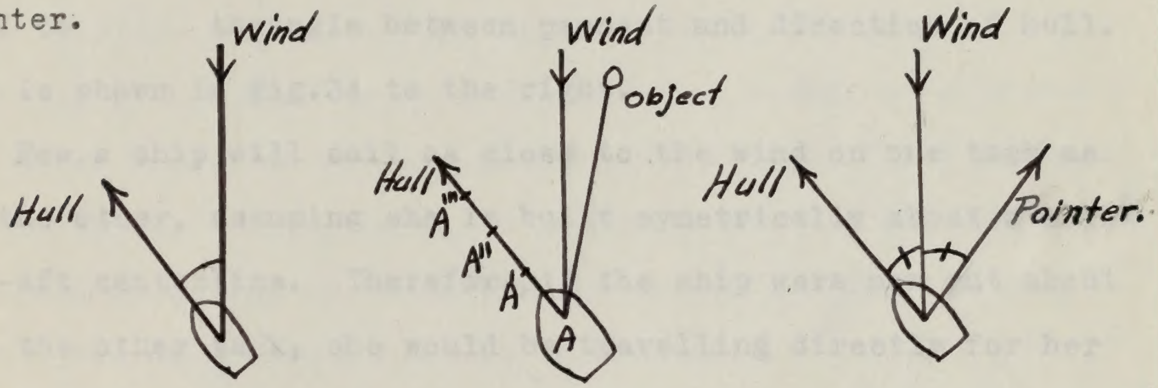


Fig. 34.

As long as the angle between the pennant and pointer (angle between apparent wind and objective, as seen by the ship) is less than the minimum angle allowed,for correct sailing , between pennant and hull the ship can not head directly for her objective. Rather, she must remain on automatic tacking control.

Referring to fig. 34 it can be seen that as the ship sails along, its course remaining unchanged, it arrives successively at points A, A', A'', and A''', During this the angle between wind and hull (actually between pennant and

the direction of sailing) and the pennant (or apparent wind direction) when the ship is pointing her highest. This is the angle the ship will set herself onto(method not yet described) when on automatic tacking. It is the angle shown in fig. 34, at the left. (2) the other angle is that between pennant and pointer. This is shown in fig. 34, at the center.

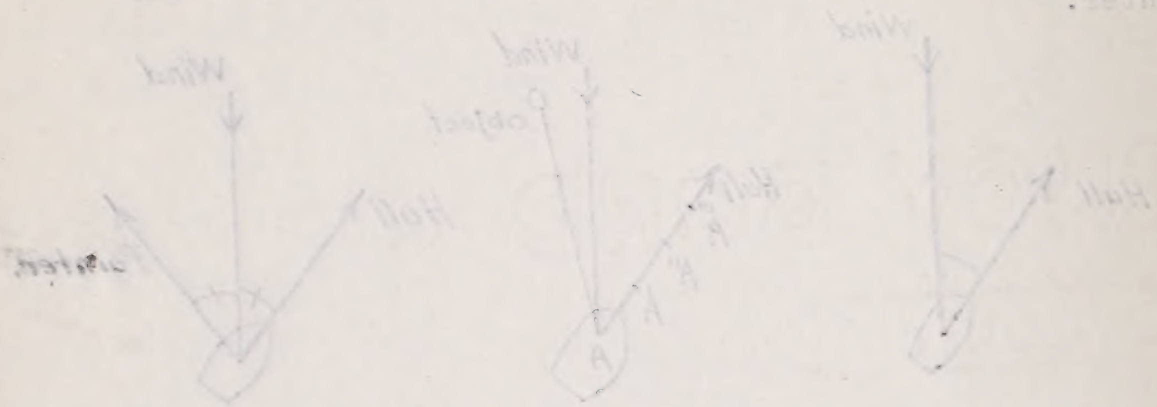


Fig. 34

As long as the angle between the pennant and pointer (angle between apparent wind and objective, as seen by the ship) is less than the minimum angle allowed, for correct sailing, between pennant and hull the ship can not head directly for her objective. Rather, she must remain on automatic tacking control.

Referring to fig. 34 it can be seen that as the ship sails along, its course remaining unchanged, it arrives successively at points A, A', A'', and A'''. During this the angle between wind and hull (actually between pennant and

hull) being automatically held constant, the objective gradually draws abeam.

Assume that the operator keeps the pointer aiming at the objective. Then the angle between the pennant and pointer will gradually increase as the ship proceeds foreward. Eventually the angle between pennant and pointer will become equal to theangle between pennant and direction of hull. This is shown in fig.34 to the right.

Now, a ship will sail as close to the wind on one tack as on the other, assuming she is built symetrically about a fore-and-aft centerline. Therefore, if the ship were now put about onto the other tack, she would be travelling directly for her objective.

The fact that any ship will sideslip when under sail must be taken into account in the determination of the angle at which the ship will come about. This will be handled later.

It was assumed that the operator kept the pointer aimed at the objective while tacking. This requirement was imposed for tacking because the angle between compass and pointer is constantly varying while tacking, since the ship is not heading directly for her objective. That is, the pointer can not be clamped to the compass as when not tacking. However, a little experience will show the operator that nothing results from diligent care of the pointer's direction until the objective draws aft to such an extent that the angle between

hull and pointer approaches twice the angle between hull and pennant.

It is only when these conditions are approached that diligent watch of the pointer direction will repay his efforts by getting the ship to come about as soon as she can make the objective on the next tack.

The calibration of the angle at which the ship goes from tacking to non-tacking control, and vice versa, as adjusted by Rs of fig.33 is to be made when the ship is first equipped with automatic control and put in the water. It should be checked from time to time, but the operator using the ship for a few hour's sail need not be concerned about this calibration for ordinary usage. (That is, unless he is interested in maximum speed).

C. Sideslip when Tacking.

Sideslip varies from a maximum when pointing high, or wind abeam, to zero when running free, before the wind. When on automatic tacking control, the ship is always on the one point of sailing, that is, pointing high. Hence it is possible to make a correction for sideslip. Sideslip is a function of wind intensity and ship's speed, so the very particular operator may want to make allowances for change in amount of sideslip under various weather conditions.

However, lets consider allowance for sideslip under general sailing conditions, which may be made when obtaining the complete angles as read by compass through which the ship turns when coming about. It will be recalled that this angle is twice the angle between pennant and hull. In other words this angle is determined by the direction of the hull, or the "apparent"direction of motion.

The true direction of motion of the ship through the water (not over the ground, for this would involve local currents) is the vector sum of the apparent motion in the direction of the hull, and the lateral or sideward motion, or sideslip. These relationships are shown in fig. 35.

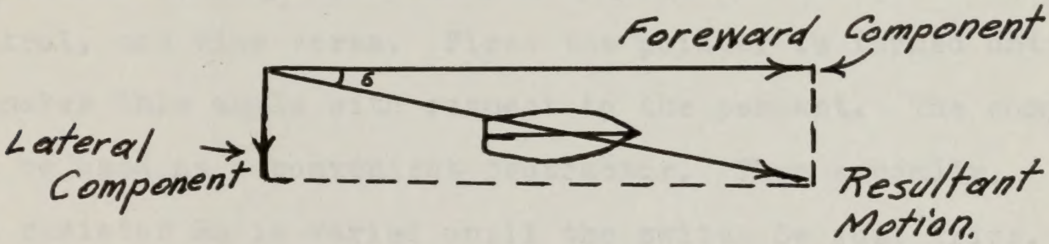


Fig. 35.

The actual angle of sideslip, shown in fig,35 may be determined by trailing along behind the ship while sailing, a long chord or rope in the water, dead astern. The angle which this chord makes with the fore-and-aft axis of the ship can then be measured, and gives a measure of the angle between desired course, and actual course due to sideslip.

This sideslip angle is than added to the total angle read on the compass(which gave the angle through which the hull itself turned when coming about). The sum of these two

However, this does not make allowance for sidewise under general conditions, which may be made when obtaining the [illegible] could be [illegible] by [illegible] through the angle [illegible] that has been set [illegible]. It will be recalled that the angle is twice the angle between point and bulb. In other words, [illegible] is only [illegible] by the [illegible] of the bulb, or the [illegible] motion [illegible].

[illegible] the [illegible] motion of the ship through the [illegible] over the ground, for this would involve local currents) is the resultant of two separate motions [illegible] direction [illegible] and [illegible] lateral [illegible] or [illegible] [illegible] relation [illegible] are shown in Fig. 25.

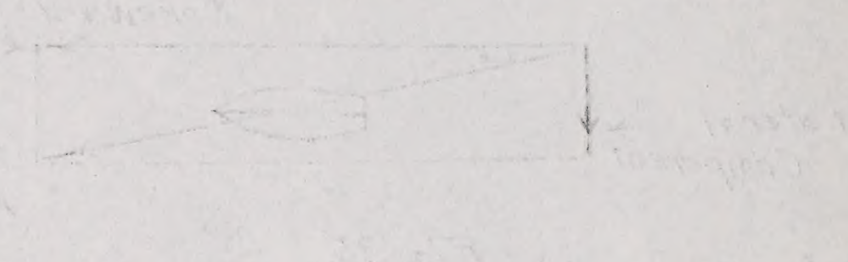


Fig. 25

The [illegible] of [illegible] (lateral [illegible]), shown in [illegible], may be determined [illegible], [illegible] the [illegible] [illegible] [illegible] [illegible]. The angle [illegible] [illegible] [illegible] [illegible] [illegible], [illegible] [illegible], [illegible] [illegible] between [illegible] [illegible] [illegible], and [illegible] [illegible] [illegible].

This [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible], the [illegible] [illegible]

is the angle of direction of motion of the ship on the new tack , not as compared with direction of motion on her present tack, but compared with the direction of hull on her present tack.

This is the angle, as read from the compass under actual sailing conditions, that Rs should be adjusted for. That is, the switch , Sw, figure 33, will change, and the critical changeover angle will be obtained when equal to the "come about" angle plus the sideslip angle.

This is very easily adjusted for. The sum of the two angles found as above is the angle between pennant and pointer for changeover from automatic tacking to automatic non-tacking control, and vice versa. First the pointer is turned until it makes this angle with respect to the pennant. The compass may be used as a convenient protractor. Then secondly, the resistor Rs is varied until the switch Sw just trips. As a check, now, the switch, Sw, should trip "out" and "in" when the pointer is turned so that this changeover angle is passed. Likewise, holding the pennant and the pointer at the critical changeover angle, the switch should drop out and in, as the resistor, Rs, is varied slightly on both sides of its value corresponding to the critical angle.

The angle between pennant and pointer, as mentioned just above, may actually be obtained for this calibration in

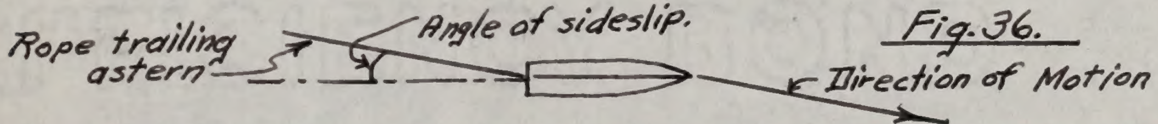


Fig. 36.

the following manner:

The ship is first secured to a dock or to some object that will prevent her from swinging too and fro, as she would when riding at her mooring. Then, a small mirror is placed on top of the compass. This mirror should not be so large as to obscure the compass from view.

Next, the image of the pennant is sighted in the mirror, and a straight thin object, such as a piece of wire, is laid on the mirror located over the center of the compass, and in line with (parallel to) the image of the pennant. This piece of wire is selected of sufficient length to compare its direction with the compass used as a protractor.

If the wind is shifty, it may be necessary for a man to go aloft and hold the pennant steady during this calibration.

The pointer is now turned until it makes the desired critical changeover angle with the pennant, and resistor Rs is adjusted as described above.

Thus the ship has an automatic control to tell her when she must tack to reach her objective, and when it is possible to arrive at her destination by sailing a straight course without tacking.

The operator on board need only aim the pointer at his desired destination as described above.

The maneuver of coming about makes use of the equipment shown in figure 37. There is a steel shade shown which serves to interrupt one or the other of two light beams coming from a "rear" set of lamps, which are in use when the ship is on automatic tacking control.

A time switch is provided which may be set at any desired interval of time between the maneuvers of coming about. When the time interval is up, and the time switch closes, it is so connected to two electromagnets, located at the sides of the steel shade of figure 37 , and to a selector switch located at the top of the mast, that the steel shade is attracted either to starboard or to port, interrupting the light beam from one of the lamps, and calling into play some motor control causing the rudder to be turned hard over.

This motor action will continue to keep the rudder turned until the ship has come about. After the ship has come about and is on the other tack the wind will be blowing from the other side of the ship. This causes the pennant to swing over to the other side. The pennant is provided with still another slider arm which makes one circuit completed when on the starboard tack, and another circuit completed when the ship is on the port tack. One circuit causes a clockwise rudder action, and the other a counter-clockwise rudder action. Once the ship swings over, and the first circuit is opened the time switch is such that it is reset to time another tack. The time switch starts counting time whenever the ship is tacking.

D. Function of Switch to Change Over Between Tacking and Non-Tacking Control.

The next problem is to see what happens when the switch, Sw, of figure 33, drops in and out. The switch is a relay switch, and is out when the ship is to be on automatic tacking control, and is in when the ship is on automatic non-tacking control. For this changeover between tacking and non-tacking control the relay switch is so arranged that it opens and closes the circuits which supply current to the lamps (one set shown in fig. 31), such that:

1) When it is out, the foreward set of lamps goes off, and the rear set goes on, placing the ship on automatic tacking control.

2) When it is in, the foreward set of lamps goes on, and the rear set goes off, placing the ship on automatic non-tacking control.

Thus the selection of controls for steering, either the automatic tacking or the automatic non-tacking controls, is made by switch Sw, and the bridge circuit of fig.33.

E. Comparison of Tacking and Non-Tacking.

When on non-tacking control the direction of the hull is dependent only on the direction of the pointer. The direction of the hull is parallel to the direction of the pointer.

However, when tacking, the pointer is aiming into the windward zone, where it isimpossibe for the ship to sail. The sails would luff if the ship were to try follow the direction of the pointer, and head up into the windward zone. Therefore the pointer must lose control when the ship goes onto automatic tacking control. The direction of the ship when tacking, in general, should be such that the wind is always inclined to the sails at a constant angle. As the wind shifts, the ship should change her direction the same amount, in order to obtain the maximum drive from the wind energy. Hence the direction of the ship's hull is controlled by the pennant when tacking.

F. Pennant Control of Ship's Direction When Tacking.

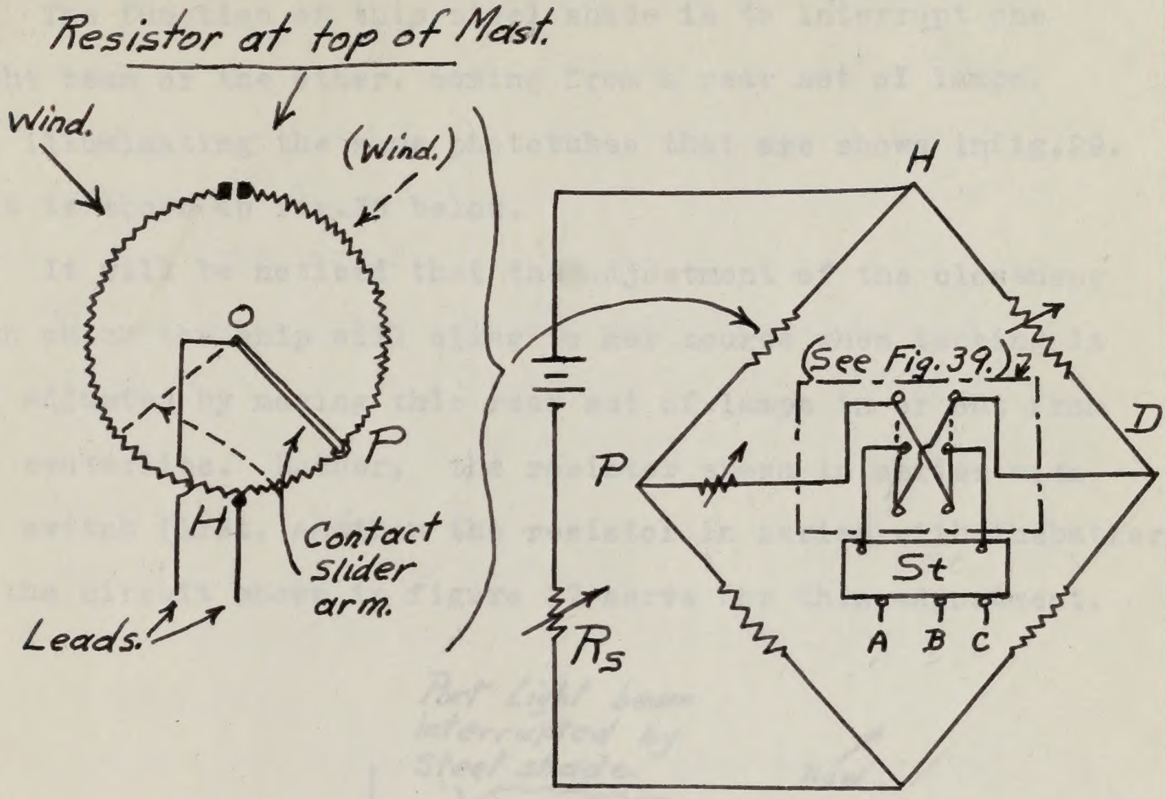
Figure 37 shows a resistor which is mounted at the top of the mast along with the other resistors there. A t point H a connection lead is taken off as shown. Also at point P a contact slider arm, connected to the pennant's shaft, and moving parallel to the pennant, taps off a n amount of resistance such that the resistance from H to P constitutes one arm of a bridge circuit. This bridge circuit is entirely separate from any previously mentioned bridge circuits. It is also shown in fig. 37 that the resistance at HP forms one arm of a bridge circuit. The other arm has an adjustable resistor. This resistor, from H to D, can be adjusted such that balanced conditions in the bridge are obtained when the

resistor at HP is such that the angle HOP at the top of the mast, the angle between pennant and hull, is equal to the correct angle for tacking.

Hence in order to decrease the angle between pennant and hull at which the ship will sail when tacking, that is, in order to make the ship point higher when tacking, resistor HD is decreased. Likewise, if it is found that the ship would perform better if she were no heading quite so high into the wind when tacking, all that need be done is to increase the resistor at HD. This would in turn require a greater resistance at HP for balance, and the ship would not point so high.

In the bridge circuit of fig 37 is also shown a relay switch, S_t. This is so constructed that:it is open when neutral, when the current in branch PD is less than a certain value; contacts AB are closed when the current in PD increases in one direction, leaving CD open; and contacts at CD close leaving those at AB open when the current reverses in PD.

When AB is closed its circuit is completed, and the steel shade is attracted to the left by the electromagnet shown. When both AB and CD are open the steel shade swings down into a vertical, or neutral position. Both gravity and a spring are used to hold the shade in the vertical neutral position. When CD is closed, and AB is open, the circuit of CD is completed, and its electromagnet attracts the steel shade to the right.


Resistor at top of Mast.
Wind.
(Wind.)
O
P
H
Contact
Slider
arm.
Leads.
H
(See Fig. 39.)
D
P
St
A B C
R_S

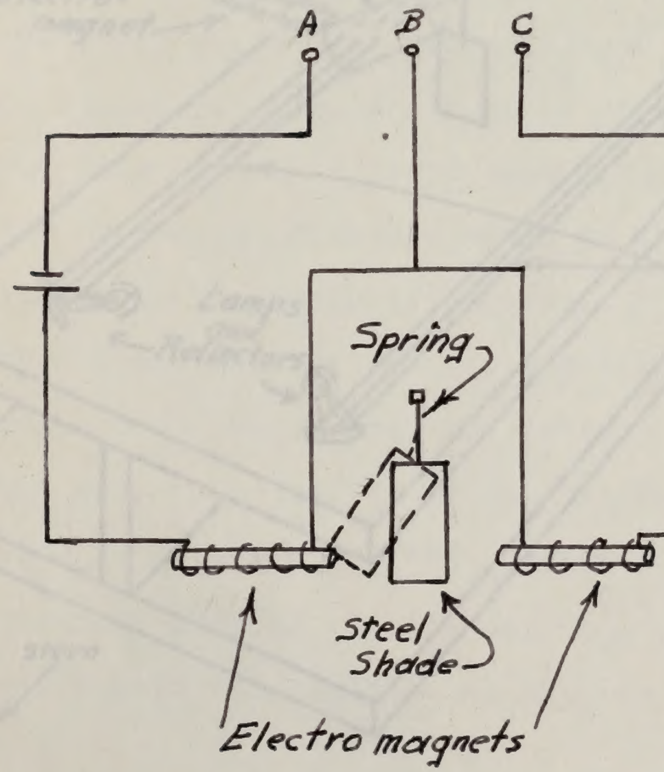

A
B
C
Spring
Steel
Shade
Electro magnets

Fig.37.

The function of this steel shade is to interrupt one light beam or the other, coming from a rear set of lamps, and illuminating the same phototubes that are shown in fig.29. This is shown in fig.38 below.

It will be noticed that the adjustment of the closeness with which the ship will cling to her course when tacking is not adjusted by moving this rear set of lamps in or out from the centerline. Rather, the resistor shown in series with the switch first, and then the resistor in series with the battery of the circuit shown in figure 37 serve for this adjustment.

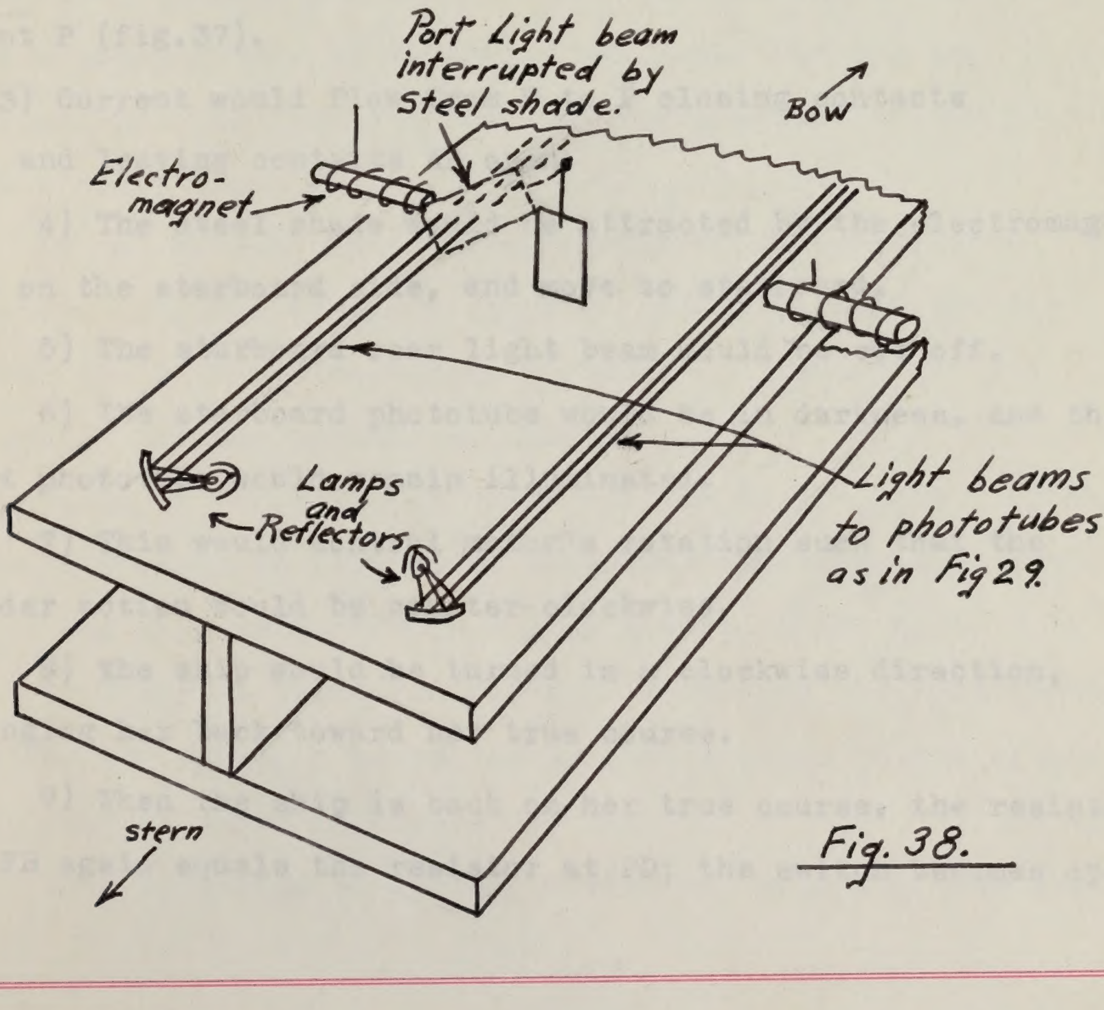


Fig. 38.

As the ship starts to deviate from her course in one direction or the other, while tacking, the steel shade of figure 37 will interrupt one light beam or the other, causing motor action to turn the rudder so as to restore the ship to her true course.

For an illustrative example, assume that the ship is travelling on a starboard tack, and happens to fall off too far, ie. turns too far in a counter-clockwise direction. Then the reactions would be:

1)Resistor at PH would increase.

2) Point D would be at a higher potential than point P (fig.37).

3) Current would flow from D to P closing contacts BC, and leaving contacts AB open.

4) The steel shade would be attracted by the electromagnet on the starboard side, and move to starboard.

5) The starboard rear light beam would be cut off.

6) The starboard phototube would be in darkness, and the port phototube would remain illuminated.

7) This would control motor's rotation such that the rudder action would be counter-clockwise.

8) The ship would be turned in a clockwise direction, bringing her back toward her true course.

9) When the ship is back on her true course, the resistor at PH again equals the resistor at PD; the switch becomes open;

the electromagnet becomes de-energized; the steel tacking shade falls to the vertical position; both phototubes become illuminated; and the rudder action is again zero as the ship sails along her course.

G. Pennant's Control of Ship's Direction on "Other Tack".

In the previous example the ship was considered on the starboard tack. When the ship is on the other tack, the port tack, the corrective rudder action must be in just the opposite direction. For example, when tacking on the port tack if the ship should fall off too far, now in a clockwise direction, a clockwise rudder action would be required to turn the ship in a counter-clockwise direction back onto her course. This is just the opposite from the requirements of the previous illustrative example.

It can be seen that the magnitude of the resistance inserted into the bridge circuit of fig.37 is the same for either the port or the starboard tack, and depends on the direction between pennant and hull.

Hence if the ship falls off too far on the port tack the current through PD will be in the same direction as it would be if the ship fell off too far on the starboard tack.

In order to provide a means of reversing the rudder action for the two tacks, a reversing switch is added in the branch PD. This is shown in figure 39.

This reversing switch is located at the top of the mast

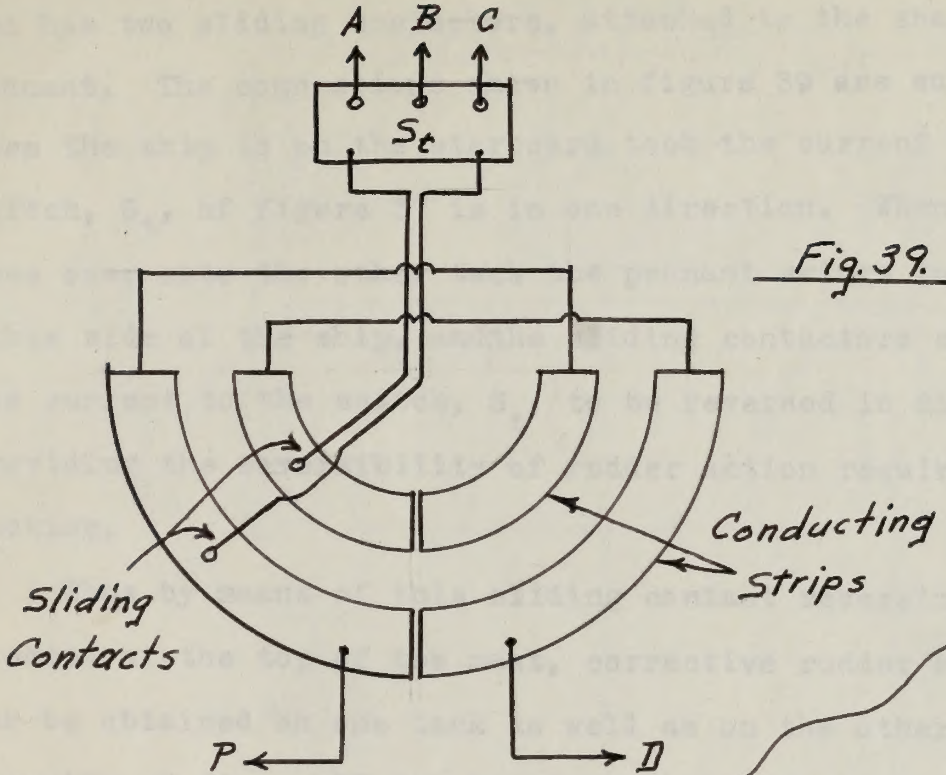

A
B
C
S_t
Conducting
Strips
Sliding
Contacts
P
D

Fig. 39.

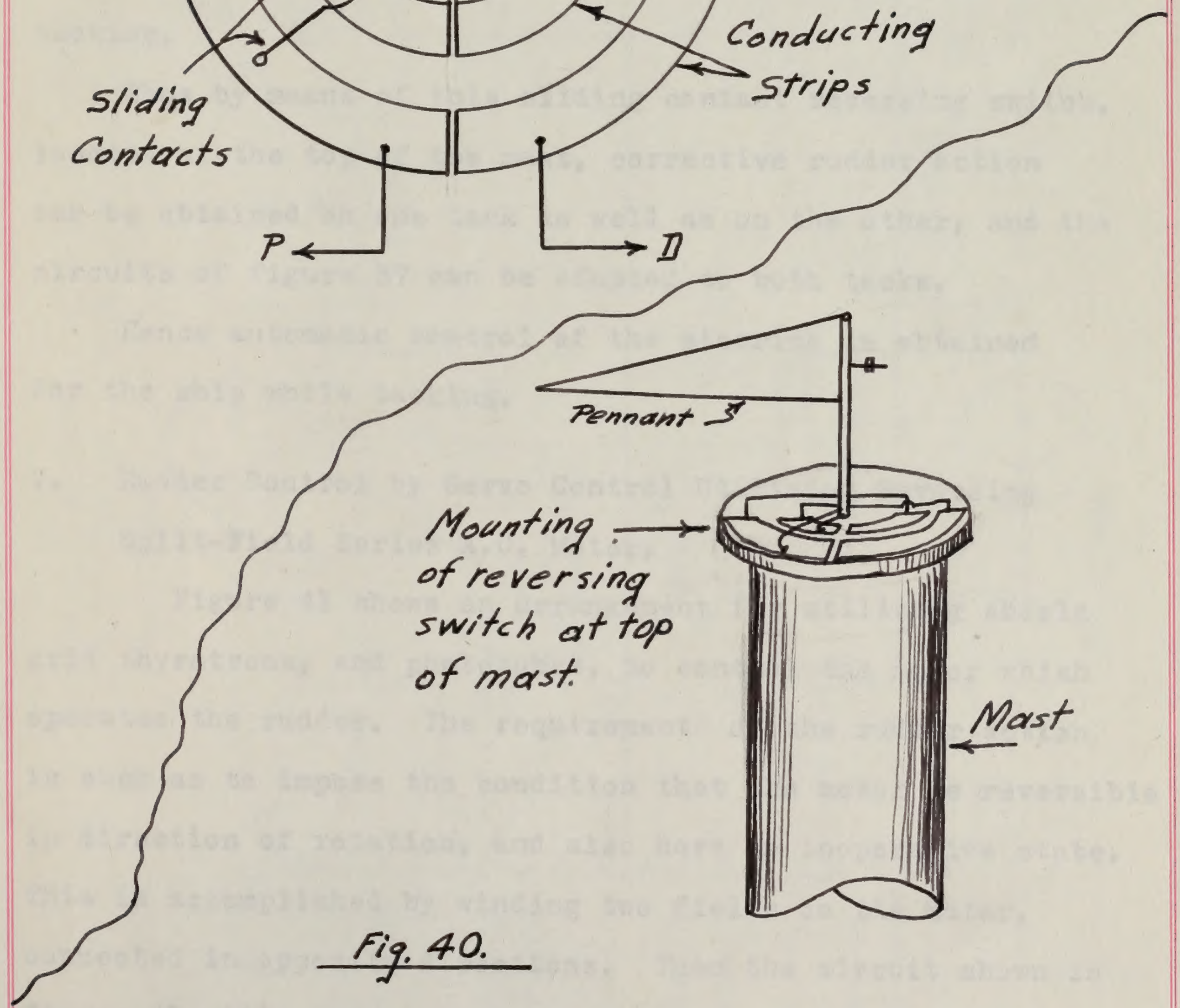

Pennant
Mounting
of reversing
switch at top
of mast.
Mast

Fig. 40.

and has two sliding contactors, attached to the shaft of the pennant. The connections shown in figure 39 are such that when the ship is on the starboard tack the current to the switch, S_t, of figure 37 is in one direction. When the ship goes over onto the other tack the pennant swings to the other side of the ship, and the sliding contactors cause the current to the switch, S_t, to be reversed in direction, providing the reversibility of rudder action required when tacking.

Thus by means of this sliding contact reversing switch, located at the top of the mast, corrective rudder action can be obtained on one tack as well as on the other, and the circuits of figure 37 can be adapted to both tacks.

Hence automatic control of the steering is obtained for the ship while tacking.

V. Rudder Control by Servo Control Utilizing Reversing Split-Field Series A.C. Motor.

Figure 41 shows an arrangement for utilizing shield grid thyratrons, and phototubes, to control the motor which operates the rudder. The requirement of the rudder action is such as to impose the condition that the motor be reversible in direction of rotation, and also have an inoperative state. This is accomplished by winding two fields on the motor, connected in opposite directions. Then the circuit shown in figure 41 will send current through just one of the fields

SERVO CONTROL UTILIZING REVERSING SPLIT-FIELD SERIES A.C. MOTOR.

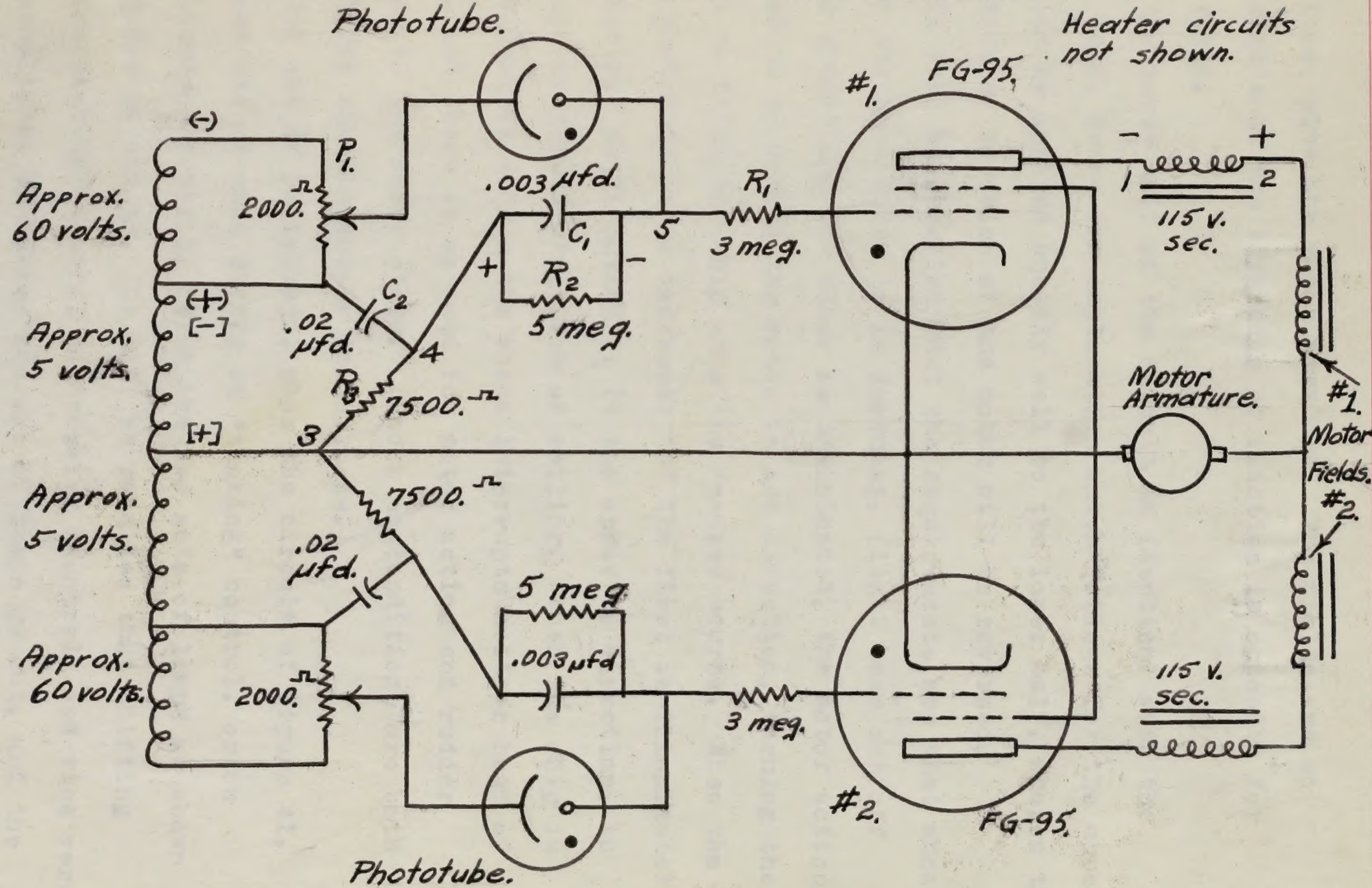


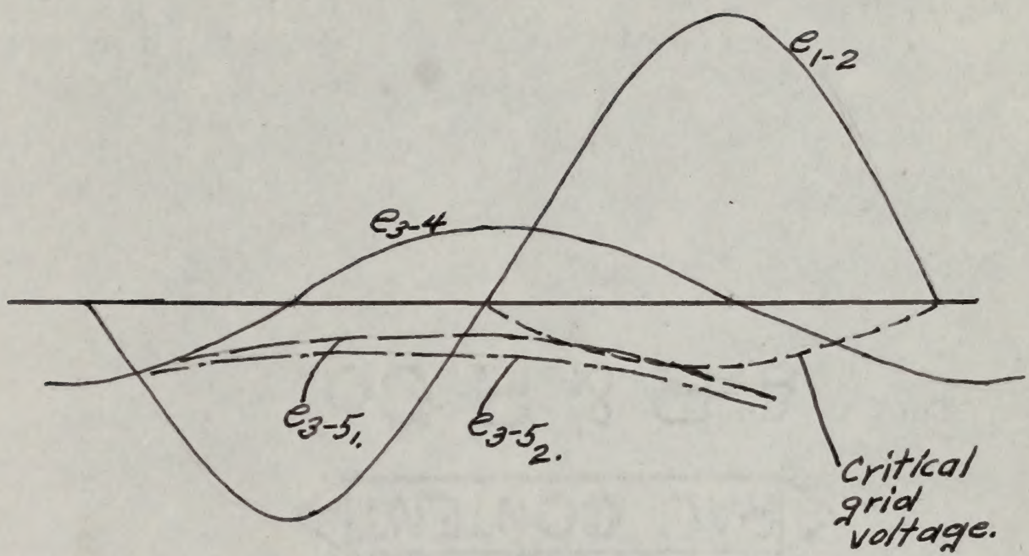
Fig. 41.

at a time, plus the motor armature. The fields are so connected that the direction of rotation is opposite for each field.

The lower half of the circuit is identical with the upper half, hence the explanation which follows for the upper half can be applied equally well to the lower half, whence the direction of rotation of the motor will be reversed.

It will be recalled that the requirements are that when one of the phototubes is in darkness, (light beam cut off by the shade) and the other is illuminated, the motor action is such as to rotate the motor in one direction, turning the rudder to bring the ship onto the desired course. When the other phototube is in darkness, and the first is illuminated, the required motor action is in the opposite direction, to correct the ship's direction of sailing. When the ship is on the desired course the shade interrupts neither beam of light, and there is no need for motor action and rudder action, so the motor stops. (Under no conditions are both phototubes simultaneously in darkness.)

One set of phototubes, plus the circuit of figure 41, are made use of when either on "tacking" control, or on "non-tacking" control; using the two sets of lamps as shown in figures 29 and 38. It will be recalled that shifting from"non-tacking" control to "tacking "control, and vice versa is accomplished by making one set of lamps go out, and the



e_{1-2} Anode voltage

e_{3-4} Fixed grid phase advance

e_{3-5_1} Grid potential, low light, motor energized, one direction

e_{3-5_2} Grid potential, high light, motor stopped.

(Same curves apply for tube # 2.)

Fig. 42.

other set go on at the same time. The phototubes, and the circuit of figure 41 never "know" which set of lamps they are working from. Thus the shift from "non-tacking" control to "tacking" control, and vice versa can take place with no interruption at all of the motor and rudder controls.

In figure 41 all secondaries are wound on the same core, and use the same primaries. The transformer polarities shown are instantaneous values.

Assume that the phototube is in darkness, and that there is no charge on C_1. The potential of the thyratron grid will be approximately that of point 4 (with respect to its cathode). Point 4 is at the junction of C_2-R_3 which forms a fixed phase shift circuit. The impedance of the capacitor is chosen to be large. Since the impedance of the capacitor at 60 cycles is about 150,000 ohms, and the resistor is only 7500 ohms, and the capacitor current leads the driving voltage by approximately 90 degrees, it follows that the IR drop in R_3 produces a low grid voltage almost 90 degrees in phase ahead of the thyratron anode voltage.

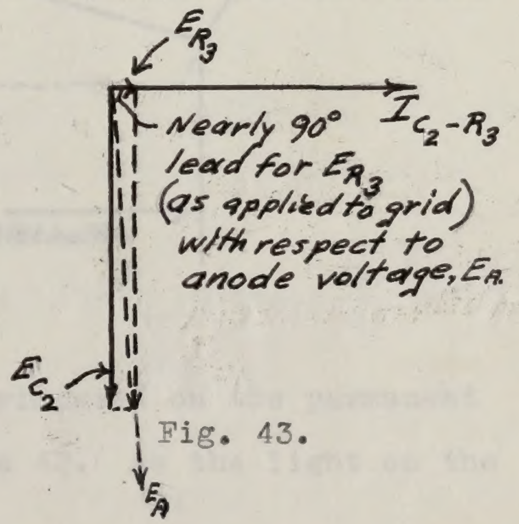


Fig. 43.

This is shown in figure 43. This leading voltage on the grid ensures that the thyratron will be conducting for the full half cycle when operating along the e_{3-5_1} curve of figure 42.

"Light on" condition- When light falls on the phototube, the phototube will be permitted to conduct on the inverse half cycle of the thyratron, charging up C_1, with the negative potential at the phototube anode, (and at the thyratron grid), as indicated. The time constant of the R_2, C_1 combination is .003 ufd X 5 megohms = .015 second, or almost one cycle of a 60 cycle wave. Thus the phototube charges up the capacitor each inverse half cycle, and the capacitor discharges along the fairly steep curve during the half cycle in which the thyratron might be conducting.

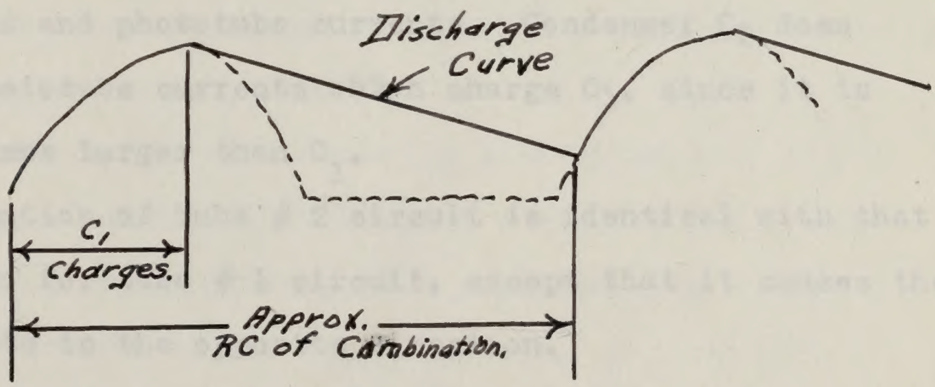


Fig. 44.

The discharge curve is superimposed on the permanent phase-shift curve shown in figure 42. As the light on the

phototube increases, the charge on C_1 is increased, and the whole grid potential is drawn more negative, to turn off the thyratron. However, because of the leading phase components, the grid potential will be most positive near the start of the positive anode cycle. Hence the thyratron will conduct for almost the full half cycle if it conducts at all. Thus the motor will not receive partial currents, and will run more smoothly.

The potential applied to the phototube, as determined by the position of the slider on the potentiometer, P_1, sets the light level at which the motor operates. It will also allow the two sides of the circuit to be balanced with respect to one another, although this adjustment need not be critical.

In figure 41, R_1 is a protective resistor to prevent excessive grid and phototube currents. Condenser C_2 does not effect phototube currents which charge C_1, since it is nearly ten times larger than C_1.

The operation of Tube # 2 circuit is identical with that just described for tube # 1 circuit, except that it causes the motor to rotate in the opposite direction.

With the light on both cells, the motor will not rotate because both thyratrons are non-conducting.

The large grid resistor that can be placed in a shield grid thyratron to provide a grid voltage component from the

small phototube currents, make it possible to have a phototube directly operate a thyratron.

VI. Auxiliary Controls.

Additional automatic controld could be made use of to supplement those described. Among these would be controls for luffing when in sqully or heavy weather, for providing automatic reefing, making use of the present day roller reefing gear, control of centerboard for racing yachts (means for raising and lowering when on the various points of sailing),automatic ballast shifting, and mast and stay adjusting for proper balance of the center of effort and center of lateral resistance.

A ship provided with automatic control might also be made completely automatic and remote controlled as well, by controlling the course by radio. Such a ship, if provided with radar and sonar equipment could also do her own watching out for obstacles in her path.

Such a remote and automatically controlled ship might be used to carry cargoes on a regular route, or for great distances with either no crew, or a skeleton crew. This would mean a savings to the ship's owners. A turnabout might be affected, with the sailing vessel utilizing wind energy replacing the steam and diesel driven ships, because the owners would then not have to pay the large expense of the fuel required to drive the steam and diesel ships.

Findings and Conclusions.

It is found that automatic control of a sailing vessel driven by wind power would require a means of controlling the trim of the sails, and a means of steering the ship. The sails must at all times be inclined to the wind at an optimum angle. This angle is not a constant value, but varies in a non-linear manner with the direction of sailing. As the ship changes course, or as the wind shifts, the sails must be re-adjusted to each change in order to obtain the maximum driving power from the energy of the wind.

It is found that the steering problems can be treated in a twofold manner: the steering when tacking, and when not tacking. These two sailing conditions impose different requirements on the automatic controls used.

In conclusion the manner of operating the automatic controls makes use of balanced and unbalanced conditions in bridge circuits. The desired, or normal operating conditions in the bridge circuits are obtained when balanced conditions are ~~obtained~~. Any deviation of the ship from its true course, or any change in the wind direction introduces unbalance in the bridge circuits which causes corrective motor action to readjust the sails, or to turn the rudder to steer the ship onto the desired course, until balanced conditions are again obtained. When balanced conditions again exist the motor action ceases, since the ship is again on her course and sailing correctly under wind power. An electronic circuit controls the rudder motor.

Comprehensive Abstract of the Thesis.

In this thesis a description is given of a method of automatically controlling a ship which is sailing under wind power. The trimming of the sails, and steering of the ship are done by automatic control equipment. Bridge circuits are used, in which the resistance of the branches are functions of the wind direction as indicated by a pennant located on top of the mast, the direction in which the ship is heading, and the direction in which the destination lies with respect to the ship. This last direction is indicated by the operator of the ship by aiming a small pointer, located on board ship, in the direction he wishes the ship to travel. When the relationships between these various angles are such that the ship is on her course, and her sails are trimmed correctly, the resistances introduced into the bridge circuits are such that balanced conditions exist. However, when the ship deviates from her true course, or the course is changed by the operator's aiming the pointer in a different direction, or the wind shifts, the resistances in the bridge circuits change, and unbalanced conditions exist within the bridges.

Unbalanced conditions in the bridge circuits bring motor controls into play. The motors adjust the sails, and turn the rudder as required to restore the ship to proper sailing trim.

An electronic circuit, using phototubes and shield grid thyratrons, plus a split field reversing A.C. series motor are used to obtain motor control for the rudder.

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An electronic circuit, using phototubes and shield grid thyratrons, plus a split field reversing A.C. series motor are used to obtain motor control for the rudder.

The operator only has to aim a small pointer, located at the compass on board ship, in the direction he wishes the ship to travel. The automatic controls and the wind do the rest.

Calibration of the ship, that is, the adjustment of the closeness with which she will adhere to ideal or best operation and the length of time she will remain on a tack, can be made before the ship is taken out for a sail.

The proper set of the sails is dependent upon the direction of the wind with respect to the direction of the ship. A bridge circuit is made use of here. The resistance in one branch of the bridge is located at the top of the mast, and is a function of the angle between the apparent wind as indicated by a pennant on top of the mast and the direction of the ship's hull.

The other variable resistor in this bridge circuit is located near the inner end of the boom, and is a function of the angle between the sail and the hull. The difference between these two angles is the angle between the wind and the sail. For best driving power the wind will be inclined to the sail at a small angle, in the order of ten degrees, when the ship is sailing close hauled, and will gradually increase as the ship is turned so as to sail more in the direction of the wind. The angle at which the wind should strike the sail thus increases until it is in the order of

ninety degrees when the ship is running before the wind.

However, the rate of increase of the angle between wind and sail is not a linear function of the angle between the wind and the hull. In order to introduce the proper non-linearity into the control of the sails, a cam, which is turned by the boom, is used. The cam adjusts the amount of resistance introduced in the arm of the bridge corresponding to the set of the sails. The control of the sails is left to this bridge circuit under all conditions of sailing. However, the control of the steering is divided between two sets of automatic controls.

The first is the control of the ship's direction when she is not tacking, and the second is the control of the ship's direction when it is necessary to tack in order to reach her destination.

When it is not necessary to tack, the ship can head directly for her objective. The operator merely aims the pointer in the direction in which he wishes to sail, and the ship heads in that direction, the sails adjusting themselves as the ship turns. The direction of the ship is dependent only on the direction of the pointer. The pointer may be turned in the desired direction, and then remain clamped to the compass which keeps the pointer in the desired direction. To the pointer is connected a shade, so arranged that as the ship deviates from her true course the shade interrupts one of

two beams of light which are directed onto phototubes. These phototubes in turn act as a motor control to turn the rudder until the ship is restored to her proper course.

However, when the objective lies directly to windward, or in a certain zone each side of this direction, the direction of the ship can no longer be controlled by the direction of the pointer. If the pointer were aimed directly to windward, and the ship turned in this direction, her sails would flap in the breeze, and no driving power would be obtained from the wind. Therefore, a different set of steering controls, known here as automatic tacking controls, must take over when the objective lies in the windward zone.

When tacking, the direction of the ship is a function of the direction of the wind. The angle between wind and hull is to remain a constant, and the ship is to change her direction for each fluctuation in wind's direction. (In this way she will get the most out of the available wind). Steering control is now obtained from another bridge circuit, having but one variable resistor. This resistor is located at the top of the mast, and is dependent for its value on the direction between the pennant and the hull. When this resistance becomes more, or less, than a certain value, a switch which is reversible, in the circuit is closed , bringing into play one of two screens to interrupt other light

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beams, which energize phototubes acting as motor controls of the rudder. The angle which the ship is to maintain between wind and hull when tacking is adjusted for by varying another resistor in this bridge circuit.

Currents through this bridge circuit are reversed when the ship is on opposite tacks. Therefore, in order that similar correct control of the ship's course while tacking be obtained, a sliding contact reversing switch is provided at the top of the mast, and is actuated by the pennant.

The ship must "know" when she can sail directly for her objective, and when she has to go onto automatic tacking control to reach her objective. Another bridge circuit is provided to facilitate this. The resistors in this circuit are functions of the angle between the pennant and the pointer, such that when this angle is less than a critical changeover angle, the ship is on automatic tacking control, and when the angle is greater than this critical changeover angle, the ship is on automatic non-tacking control.

In order to make the ship actually come about onto the opposite tack, a time switch is provided, which is in operation as long as the ship is on automatic tacking control. This switch may be set for any desired time interval between tacks. The equipment used for motor control of the rudder when on automatic tacking control is utilized to make the ship come about.

Thus a ship is provided with automatic control for adjusting the sails and steering, while the operator just aims a pointer in the direction he wishes to travel.

Other auxiliary equipment could be used to supplement these controls. Among these would be automatic controls for; reefing making use of the modern roller reefing gear, luffing, controlling the height of the centerboard for various points of sailing, ballast shift, backstays, bailing, and hoisting sail.

Radar, sonar, and remote radio control, together with the automatic control, may conceivably provide a means of transporting materials by water over long distances on a crewless, or "phantom" ship. The savings to her owners over a period of time may justify a turnabout, with the sailing vessel, which makes use of automatic control of wind energy, replacing the more obsolete steam and diesel-driven rovers of the deep.

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